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September 2000

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IDA Paper P-3552

Log: H 00-002035

This work was conducted under IDA's independent research program, CRP-2038. The publication of this IDA document does not indicate endorsement by the Department of Defense, nor should the contents be construed as reflecting the official position of that Agency.

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PREFACE

This work was supported by a Central Research Project (CRP) at the Institute for Defense Analyses (IDA).

ACKNOWLEDGMENTS

We would like to acknowledge the assistance of the following individuals and organizations in the preparation of this paper (alphabetical by organization): Shoko Yoshikawa at Active Control eXperts, Inc.; Spencer Wu at the Air Force Office of Scientific Research; Greg Agnes at the Air Force Institute of Technology; Keith Denoyer, Rory Ninneman, Brian Sanders, and James Tuss at the Air Force Research Laboratories; Bob Ormiston at the Army/NASA-Ames; Gary Anderson at the Army Research Office; Jim Shoemaker at Ballistic Missile Defense Organization; Friedrich Straub at Boeing (Mesa); Mark Hopkins and Ed White at Boeing (St. Louis); Aaron Bent at Continuum Control Corp.; Eric Anderson at CSA Engineering; Ephrahim Garcia at the Defense Advanced Research Projects Agency (DARPA); Jeff Hall at Electric Boat; Porter Davis and Jack Jacobs at Honeywell; Felicia Brady, Anthea DeVaughan, Chuck Everett, and Dee Saunders at IDA; Bernie Carpenter and Suraj Rawal at Lockheed Martin Astronautics; Steve Winzer at Lockheed Martin-Palo Alto; Kent Murphy and Mike Gunther at Luna Innovations; Steve Hall and Eric Prechtl at MIT; Don Krantz at MTS Corporation; Keith Belvin, Jennifer Florance, Joycelyn Harrison, Jennifer Heeg, Garnett Horner, Lucas Horta, Anna McGowan, Bob Moses, Sharon Padula, Darrel Tenney, and W. Keats Wilkie at NASA-Langley; Bob Badaliance, Lee Gause, and John Michopoulos at Naval Research Laboratory; Thang Nguyen at the Naval Surface Warfare Center-Carderock; Jay Kudva at Northrop Grumman; Jim Kelly, Pat Purtell, Wally Smith, and Kam Ng at the Office of Naval Research; Thomas Shrout at the Pennsylvania State University/Materials Research Laboratory and TRS Ceramics; Marc Regelbrugge at Rhombus Consultants Group; Dave Flamm and Ken Chou at SRI International; Doug Lindner at Virginia Polytechnic Institute and State University; Troy Schelling at Virginia Power Technologies; and Ben Wada (retired consultant).

The financial support of IDA under project CRP-2038 is gratefully appreciated.

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I. INTRODUCTION

During the past decade, the multidisciplinary field of smart materials and structures has experienced rapid growth in terms of individual technologies and applications. The integration of sensors, actuators, and controllers with structures that enable adaptation to environmental and operational conditions has progressed to such a point that numerous systems applications are being demonstrated. This paper reviews the results to date, current status, and issues associated with several of these projects. This review is not comprehensive to the entire body of literature but, instead, focuses on realistic sub- or full-scale systems demonstrations and relevant characterization and testing. The status of individual technologies important to achieving the ultimate objective of a "smart" system is also addressed in some detail. [1]

The idea of synthesizing smart materials and structures dates at least as far back as 1968 [1] when Henry Clauser published this idea in a broad, conceptual form. By 1975, Clauser had fully developed the concept of engineered materials as dynamic systems that could replace mechanical and electrical components and respond to service conditions [2]. By 1978, the idea had received international attention. R.L. Forward was among the first researchers to investigate the possibility of using piezoceramic devices as passive dampers in mechanical systems, and he patented several innovative concepts in the late 1970s [e.g., 3–5]. In 1983, Forward, Swigert, and Obal [6] completed one of the first successful vibration-control demonstrations using surface-mounted piezoceramic sensors and actuators. A substantial amount of jitter reduction was achieved on a cavity resonator mirror by combining a passive-tuned mass damper with an active-rate feedback vibration-control network that included piezoceramic devices. Following these early efforts, much of the work into the early 1990s focused on vibration-suppression applications in spacecraft. This work was funded primarily by the Ballistic Missile Defense Organization (BMDO), then the Strategic Defense Initiative Organization or SDIO, and the Air Force [e.g., 7–11]. The bulk of work in this field has been supported by the Department of Defense (DoD), for reasons that will become obvious.

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1 We cannot emphasize too much the large volume of papers published in the relevant technical areas each year. This does not permit a comprehensive review. At best, several references can be suggested to provide a good starting point.

In 1993, the Defense Advanced Research Projects Agency (DARPA) recognized that smart materials and structures technology provides a specific opportunity for many technological breakthroughs. An 8-year program was initiated to develop new, affordable smart materials and structures and to demonstrate the performance gains achievable in system applications. The focus of the DARPA program is to use smart materials to achieve aerodynamic and hydrodynamic flow control and to reduce noise and vibration in a variety of structures. A portion of this effort has also been directed toward improving the authority of actuation materials and their use in actuators to expand the potential applications of the technology. In a recent follow-on program, these smart materials are being combined with other actuation techniques and appropriate power and control electronics to make unique, compact hybrid devices for a variety of defense applications.

Since the early 1990s, the Army has supported more basic research in smart structures and materials. Current efforts of the Army Research Office (ARO) in the smart structures area include vibration suppression, noise reduction, antenna shape control, health monitoring, and nonlinear control systems. Many of these programs focus on helicopter performance issues. Other groups in the Army are addressing advanced rotary wing concepts, including active on-blade control and active blade twist and vibration issues for large guns. Since the early 1990s, the Air Force, the National Aeronautics and Space Administration (NASA), and the Navy have also initiated several programs to demonstrate the application of smart structures in a variety of systems—most specifically, fixed-wing aircraft, helicopters, spacecraft, missiles, and submarines. For example, NASA has worked closely with the Services (Air Force and Army) and DARPA to address specific problems on aircraft and helicopters. They have also initiated programs to investigate the application of these and other advanced technologies to new aircraft and spacecraft concepts. These and related Air Force efforts are focused on aerodynamic flow control, vibration and noise suppression, and optimization of lifting surfaces. They also include modifying structural dynamics and aeroelastics, providing for flight path controls, and integrating electronics into structures [12]. In addition, the Navy has funded significant work in the development of actuator materials, especially ceramics and, most recently, single-crystal piezoceramics. Other focus areas for the Navy include structural health monitoring via fiber optics; control of large precision spacecraft; and hydrodynamic flow control, vibration and noise suppression, and optimization of lifting surfaces for underwater vehicles.

The idea of using adaptive structures to improve the performance of military aircraft is not new. A joint NASA/Wright Laboratory demonstration program—the

Mission Adaptive Wing, flight-tested during the 1980s on an F-111A test aircraft—investigated active control of chordwise camber, spanwise camber, and wing sweep while maintaining a smooth, continuous airfoil [13–16]. Variable leading and trailing edge shapes were of particular interest. Shapes with large camber, large leading-edge radii, and large depths are desired for low-speed flight because they provide high maximum lift coefficients. In high-speed flight, on the other hand, drag becomes the dominant parameter; therefore, low camber, small leading-edge radii, and shallow depths are highly desirable. Observed benefits for the F-111A wing with variable leading and trailing edges were improved performance and terrain-following, control of maneuver loads, and reduced radar cross section (RCS). While stealth and aerodynamic benefits were achieved, the devices and linkages needed to obtain the shape changes were so complicated as to be impractical for implementation.

At present, there are three approaches to the development of smart materials and structures. The first approach attempts to synthesize new materials at the atomic and molecular level to produce new materials with smart functionality. The success of this approach will depend on new scientific discoveries. As a result, the technologies derived from this approach are very immature. For the second approach, actuators and sensors are attached to a conventional structure. This approach is the most mature, but the active components are parasitic to the structure, a feature that may make it less attractive for implementation and that does not take full advantage of potential "smart" systems capabilities. The third approach attempts to develop new materials by synthesizing composite systems from known materials. These composites contain active constituents (sensors and actuators) and are used to fabricate the structure. The conceptual difference between the latter two approaches is as follows: by adding parasitic sensors and actuators (second approach), the control system makes the structure respond; by integrating sensors and actuators into the material itself to form a composite (third approach), the *material* responds to the control system.

Sensors include conventional strain gages, fiber optics, and piezoelectric ceramics and polymers, among others.[2] Embedded sensors can be used in discrete or distributed locations to provide built-in structural quality assessment during composite processing and during system operation. For system performance, it is important that the right features be measured by the sensors and that the signal be interpreted with respect to the

2 Microelectromechanical systems (MEMS) sensors offer some attractive possibilities for smart structures.

desired performance outcome.[3] Typical smart structure actuators are shape memory alloys (SMAs), piezoelectric and electrostrictive ceramics, and magnetostrictive materials. When combined with a sensor/signal processing network and an appropriate control system, actuators allow structural performance to be changed or adapted to meet various operational performance criteria. Actuator devices can be used either dynamically, such as for vibration suppression, or quasi-statically, such as for shape control. Electro- and magneto-rheological fluids and elastomers, although not strictly sensor or actuator materials, find use in actively changing attributes such as structural stiffness. The primary challenges are really those of designing and synthesizing the material and fabricating the structure to realize the anticipated performance gains.

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3 For example, in a shape adaptive airfoil, strain associated with curvature or deflection is measured to reflect changes in airfoil shape. In this case, the desired performance objective would be a change in lift.

II. VISION

In what application areas might these "smart" technologies provide system benefits? The range of potential applications is broad and includes structural integrity monitoring, vibration and noise suppression, shape change, and multifunctional concepts for all types of air and space vehicles.

Structural integrity monitoring represents a more near-term opportunity for implementation of smart materials and structures technologies. Recent advances in sensors, data acquisition capabilities, electronics miniaturization, and sensor system integration offer unprecedented opportunities for an integrity monitoring system [e.g., 17]. Such integrated systems could provide accurate, detailed load histories for the air or space vehicle. These histories can be used determine the location of damage,[4] thus simplifying inspection and life-cycle monitoring. This, in turn, could reduce manpower expended on current manual methods and provide significant cost savings.

Vibration problems occur in all types of air and space vehicles. When applied to structural dynamics problems, the use of smart materials and structures technology is expected to stabilize dynamic instabilities and significantly alleviate vibrations and, hence, enhance fatigue life. Vibrations, acoustics, and shock stemming from large launch loads dominate designs for spacecraft and launch vehicles. These design limitations, in turn, lead to significant, excess mass and high launch costs. Billions of dollars in lost satellites or degraded performance of precision payloads are attributable to failures arising from launch load vibrations. Acoustic signature affects military operations by increasing the detectability of air vehicles. It also affects commercial operations: high noise levels in fly-overs or landing result in limited community acceptance. Vibrations impact passenger/crew comfort and weapons accuracy, and the fatigue lives of most structural and electronic components are adversely affected. As a result, system reliability is reduced, and maintenance activity increases. Several specific vibration problems have been identified and targeted for systems demonstrations using smart materials and structures technologies. These demonstrations include precision pointing, launch isolation, isolation from shock caused by pyrotechnic release devices, isolation of

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4 It may also be possible determine the amount of damage.

electronic components from forced vibrations, interior noise suppression, tail buffet damping, wing flutter control, helicopter blade-vortex interaction (BVI), and helicopter blade tracking adjustment.

The concept of shape adaptive structures and aerodynamic flow control figures predominantly in current thinking about applications for smart materials and structures. Ultimately, the need for these concepts is driven by the fact that fixed geometry structures, such as aircraft wings and engine inlets, exhibit nonoptimal performance over a range of flight conditions, although they may exhibit exceptional performance at a specific flight condition. Design concepts of interest include wing warping, camber shaping, inlet lip blunting, and inlet wall shaping. Among the expected performance benefits are enhanced maneuverability, improved aeroelastic effects, reduced signature and drag, increased take-off gross weight, and increased range capabilities.

Other smart materials and structures concepts use multifunctional structures [i.e., structures that are designed to include multiple functional components, such as radio frequency (RF) antennas, signal processors, various types of sensors, wiring, and cabling, into a conformal structure in a smart skin]. Nonconformal, externally mounted antennas degrade vehicle aerodynamic performance, require substantial maintenance, and increase vehicle signature. Potential benefits of these integrated systems include reduced weight and volume; low observability (especially for conformal antennas); reduced energy consumption; improved system performance, including flexible capabilities to enable new missions; and lower costs because of reduced duplication and potentially easier repair and maintenance. Significant weight and volume reductions are particular advantages for spacecraft containing integrated power distribution and data transmission cabling. The need for large weight and volume reductions will become increasingly important with the advent of nanosatellites (about 10 kg) and microsatellites (about 100 kg).

What kinds of system-level benefits are expected for these smart systems? Future commercial and military air and space systems will benefit substantially from smart materials and structures technology. Expected benefits include, among others:[5]

- Allowing for "maintenance on demand" (or condition-based maintenance) by monitoring system health to include damage detection and, eventually, mitigation and repair

5 These benefits are ranked, more or less, from near term to far term.

- Increasing passenger/crew comfort by reducing interior cabin/vehicle noise
- Increasing system/component structural life by reducing structural and acoustic vibrations caused by panel flutter, buffet, BVI, and spacecraft launch environments, including those vibrations caused by other mounted components such as motors or gear boxes
- Improving precision pointing and/or sensing capabilities by reducing structural, acoustic, and shock vibrations in on-orbit spacecraft
- Enhancing aircraft and rotorcraft handling by manipulating lift or reducing drag, by changing control surface shape, or by affecting flow conditions over the lifting surface
- Improving aerodynamics and possibly enabling new flight profiles by producing twist in aircraft wings or helicopter rotor blades
- Improving aerodynamics and low observable (LO) characteristics and reducing manufacturing and assembly costs by integrating power and electronic systems into the structure.

III. SIGNIFICANT DEMONSTRATION PROJECTS

This section highlights major demonstration programs addressing structural health monitoring, vibration and noise suppression, shape control, and multifunctional structural concepts for spacecraft and launch vehicles, aircraft, and rotorcraft. These demonstrations focus on showing potential system-level performance improvements using smart technologies in realistic structures.

A. STRUCTURAL INTEGRITY MONITORING

Aircraft structural maintenance has evolved considerably since the late 1950s, when fatigue problems in aircraft were first observed. Continuous integrity monitoring of aircraft structures has received particular, significant attention [e.g., 18–20]. Recent advances in sensors, data acquisition capabilities, electronics miniaturization, and sensor system integration offer unprecedented opportunities for a Structural Integrity Monitoring System (SIMS) and, eventually, for "maintenance on demand" [e.g., 17, 21].

In general, an integrity monitoring system consists of:

- Sensors for acquisition of structural properties
- Signal acquisition and analysis electronics to process the sensor output
- A mathematical algorithm to extract information about damage in the structure.

Such integrated systems could provide accurate, detailed load histories for the aircraft and locations of damage (including the amount of damage). Large area damage, such as that which would result from gunfire, is much easier to assess. Finding small, damaged areas that may later lead to failure is a much more difficult and challenging problem.

Recent concepts look to combine local preprocessors with sensors capable of detecting loads and environments. The central processor interrogates each of the local preprocessors to obtain sensor data that are then analyzed and stored as required. This type of system offers flexibility because it can be enlarged to handle growth. Having a network of sensors also offers fault tolerance and redundancy. An issue with this approach, however, is information management. Synthesis and analysis of signals from large numbers of sensors to derive appropriate diagnostic information and prognoses are

still evolving. Efforts are currently underway to reduce the total number of sensors required by using available aircraft usage data[6] to infer stresses and damage using suitably validated parametric and analytical models.

Under a jointly sponsored Air Force/Navy program, Northrop Grumman developed and demonstrated a prototype SIMS on a simulated wing spar and a wing carry-through bulkhead (a multibay structure), as shown in Figure III-1 [17]. Results indicated that the acoustic emission (AE) sensors could detect cracks as far away as 18 in. in simple geometries, such as a wing spar web. Cracks were much harder to detect in complicated geometries, such as stiffeners between the bays in the bulkhead. For complex structures, the AE sensors had to be located within a few inches of the flaw to obtain positive identification. Fiber-optic sensors were more sensitive, detecting a small torsion in the wing spar that was not detected using conventional strain gages. These approaches were evaluated during a full-scale fatigue test of an F/A-18 wing attach bulkhead [22]. The bulkhead failed at 9,000 equivalent flight spectrum hours of loading at a somewhat unexpected location away from the sensors. The collected broadband AE data revealed growth of the failure crack at about 7,000 hours; however, since processing and pattern recognition were not automated, the crack detection was performed post-test by an AE expert.[7] Expected benefits of this technology include improved safety, reduced and simpler maintenance, and reduced life-cycle costs. Cost savings could be quite substantial: > $35 million is predicted for the F-18 (assuming 33 flight hours/aircraft/month, 1,000 in fleet) [23]; > $9 million is predicted for the T-38 (assuming 420 flight hours/aircraft, 720 in fleet) [24]. More significant savings are expected from the elimination of logistics personnel: an estimated $100,000 per year in manpower and equipment with the automation of just one logistics function [25].

Another approach that has been used is to excite the structure with piezoelectric actuators and use piezoelectric sensors to monitor the response at selected points [19]. Changes of the structural response to the excitation are measured over time and are then correlated with damage through analysis of the measured frequency response functions of the structure. This technique has been tested on a rib of the vertical fin of the ATR-42 aircraft, with good results. In this test, rivets were removed to simulate damage.

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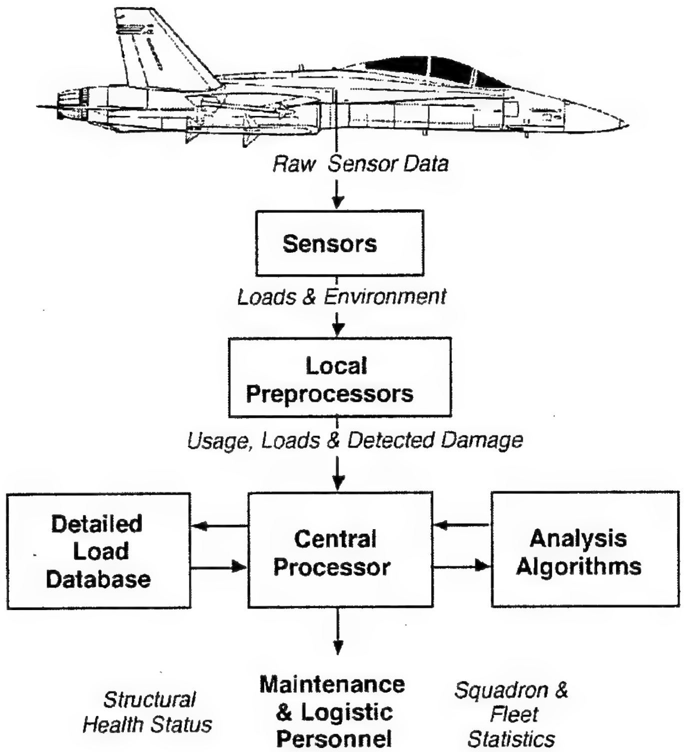
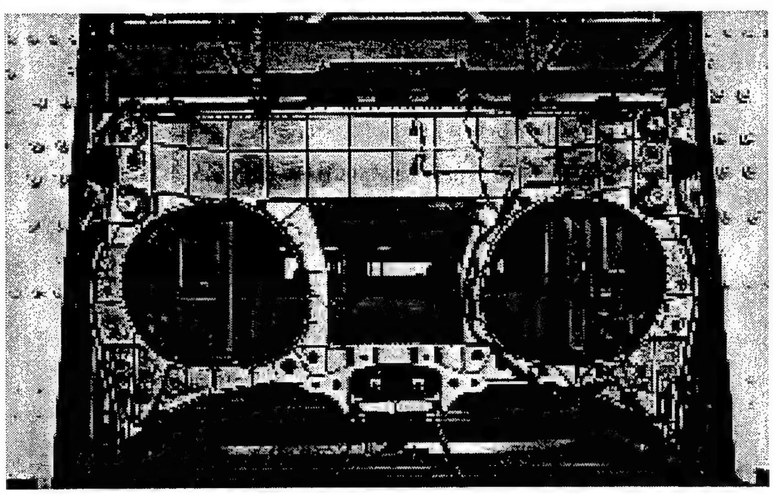
6 Typical data include altitude, Mach number, weight, fuel consumption, total flight hours, and so forth.

7 Northrop Grumman is currently developing automation routines.



(a) Overview of the Components



(b) The Wing Attach Bulkhead Mounted in the Test Frame

Figure III-1. Prototype Structural Health Monitoring System Developed and Tested by Northrop Grumman (Courtesy of Northrop Grumman)

McDonnell Douglas (now Boeing) developed a similar approach, referred to as Active Damage Interrogation (ADI). It uses an array of piezoelectric transducers—either embedded or attached to a structure—that act as both sensors and actuators [26]. This system, which is model independent, actively interrogates the structure via broadband

excitation of multiple transducers across the desired frequency range. The severity of the damage and its location are determined via statistical analysis of changes in transfer functions. The ADI methodology was successfully tested on a composite flexbeam on the MD-900 Explorer rotor system.

The SIMS for the Eurofighter 2000, being designed by British Aerospace, is an integral part of the avionics system. It consists of a set of strain gages attached to the aircraft structure to monitor cyclic strain and significant structural events. This developmental system is flexible and can be configured either as a parametric-based or strain-gage-based fatigue monitoring system. Accumulated and real-time load cycle data are analyzed to determine fatigue life consumed and to monitor significant structural overload events [27, 28]. The system is being integrated with the logistics support functions of the aircraft to minimize maintenance costs.

A Prognostics and Health Management (PHM) system is being developed for the Joint Strike Fighter (JSF). The JSF program is examining prognostic methods for analyzing the sensor data based on an artificial intelligence scheme that may use rule-based, model-based, and/or case-based reasoning; artificial neural networks (NNs); fuzzy logic; and genetic algorithms. This system will also be integrated into the logistics support for the aircraft [18]. The JSF is currently sponsoring demonstrations of appropriate sensors, signal processors, and reasoners on aircraft parts. Seeded fault experiments in jet engines are being conducted, and the data will be used to formulate and validate the models for the system. The JSF Program Office envisions that this PHM system will become part of a distributed information network that integrates diagnostic support, aviation maintenance information, and Air Force integrated information systems into a Joint Distributed Information System (JDIS) encompassing both on- and off-aircraft information.

JSF, NASA, and the Navy are supporting the development of wireless PHM sensors. Wireless data acquisition accelerometers and strain sensors for monitoring airframes have been developed and tested in a Navy flight test. Algorithms have been developed to extract relevant "features" from the data for classification. By using artificial NNs, the ability to classify maneuvers in real time has been demonstrated [29].

The Navy has supported efforts to develop remotely queried microsensors capable of being embedded into structural composites [30]. The Remotely Queried Embedded Microsensor (RQEM) program was funded by the Office of Naval Research (ONR) and led by MTS Corporation. The RQEM team also included two laboratories, three

universities, and two companies. Several prototype devices were fabricated and tested. RQEM packages are being field-tested on an AV-8B aircraft, on the experimental composite mast structure of the *USS Radford*, and in a one-half scale hull section fabricated using the SCRIMP™ process.

The rationale for applying structural integrity monitoring methodologies to aircraft applies equally as well to space systems like reusable launch vehicles (RLVs). A SIMS was developed as part of the joint Delta Clipper-eXperimental Advanced (DC–XA) reusable rocket program between NASA and McDonnell Douglas (now Boeing) [31, 32]. This system was required to monitor and validate the performance of several key advanced structural components during ground and flight tests. It was also used to assess the readiness of these same structural components to support rapid, safe, turnaround flight tests. Both fiber-optic and conventional sensors were successfully demonstrated in four flight tests, although issues associated with the installation and alignment of fiber-optic sensors still need to be resolved.

B. VIBRATION AND NOISE SUPPRESSION

When applied to structural dynamics problems, the use of smart materials and structures technology is expected to reduce dynamic instabilities and vibrations significantly (and, hence, fatigue damage caused by vibrations). Vibrations impact passenger/crew comfort and weapons accuracy, and the fatigue lives of most structural and electronic components are adversely affected. As a result, system reliability is reduced, and maintenance activity increases. Acoustic signature affects military operations by increasing the detectability of air vehicles, especially rotorcraft. It also affects commercial operations: high noise levels in fly-overs or landing result in limited community acceptance. Several specific vibration problems have been identified and targeted for systems demonstrations using these smart technologies: various spacecraft vibrations including on-orbit, launch, and shock vibrations; interior cabin noise; tail buffet; wing flutter; isolation of electronic components from forced vibrations; and helicopter BVI and blade tracking.

The Air Force and NASA, and to a lesser extent, DARPA, have supported extensive work in the area of vibration and noise suppression for a variety of applications. Specific vibration problems have been addressed to date with scaled models in various ground tests and wind-tunnel tests. Full-scale component and flight tests have also been conducted on several systems.

1. Spacecraft and Launch Vibration and Noise Suppression

Much of the early work on vibration suppression of space structures was—and continues to be—focused on directed energy weapons (DEWs) and precision sensor platforms. For the large, flexible DEW platforms, weapon effectiveness depends on sustained sub-microradian pointing accuracy against accelerating targets. The sensors are typically viewing targets that are hundreds of miles away and required tolerances are often fractions of the wavelength the sensor is built to detect, with precision on the order of millionths of a degree or tens of nanometers. These large DEW systems typically exhibit very low stiffness and light damping, factors that result in open-loop errors of the order of a football field. The structural flexibility cannot be reduced without adding mass, which is undesirable from a launch perspective. Multiple disturbance sources[8] on spacecraft can affect the performance of space-based sensor systems, and it is difficult to eliminate these vibrations completely. In addition, the increased use of lightweight, high-stiffness composite materials in new satellites gives rise to other concerns about the severity of the acoustic environment: fewer mechanical connections translate to less damping, which, in turn, implies increased vibration levels and acoustic transmission. The response to these challenging, complex problems has been a hierarchical one, incorporating passive and active vibration isolation concepts with structural control and active optics.

One of the first major demonstrations of active vibration suppression was the Advanced Composites with Embedded Sensors and Actuators (ACESA) program [8, 9], sponsored by the Air Force Astronautics Laboratory [now Air Force Research Laboratory (AFRL) at Kirtland AFB] and SDIO. This project focused on designing, fabricating, and testing graphite-epoxy composite components containing embedded piezoelectric lead-zirconate-titanate (PZT) sensors and actuators, and microprocessors in logical steps—first, demonstrating feasibility, and then fabricating and testing sub-scale and full-scale components. TRW demonstrated that precise attitude and alignment stability of a flexible structure could be enabled by an active damping/shape control system, which operates on the flexible body modes and does not interact adversely with the rigid body attitude control system.

The ACESA program culminated with the installation of three, 16-ft long, 5-in. diameter "smart struts" and custom control electronics in the Phillips Laboratory's

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8 Typical disturbance sources include solar panel arrays, attitude control devices, and cryocoolers.

Advanced Space Structures Technology Research Experiment (ASTREX) Facility (see Figure III-2). ASTREX was a ground testing facility for large-angle retargetting, precision pointing, and vibration-suppression testing on a dynamically scaled, three-dimensional (3-D) structure. The damping control system was able to eliminate first-mode vibrations within two cycles after being turned on. The 20 percent damping levels achieved represent an increase of 100X over the damping levels inherent in the structure. The project also demonstrated the ability to dampen vibrations over a frequency band from 10 to 80 Hz, with a very simple control approach. A stroke of several micrometers was achieved in the "smart" struts, with virtually no hysteresis or creep. Each active member had a high stiffness-to-weight ratio, very high levels of vibration damping through local feedback from sensors to actuators, and the capability for a limited amount of shape control by commanding the actuators from a central control computer. In addition to some fabrication difficulties, issues that became obvious with these early programs were the size and weight of the ancillary support electronics (e.g., amplifiers, processors, cabling). These would make application of this technology difficult—if not impossible—on a real system. Miniaturization of electronic devices is key to addressing this problem.

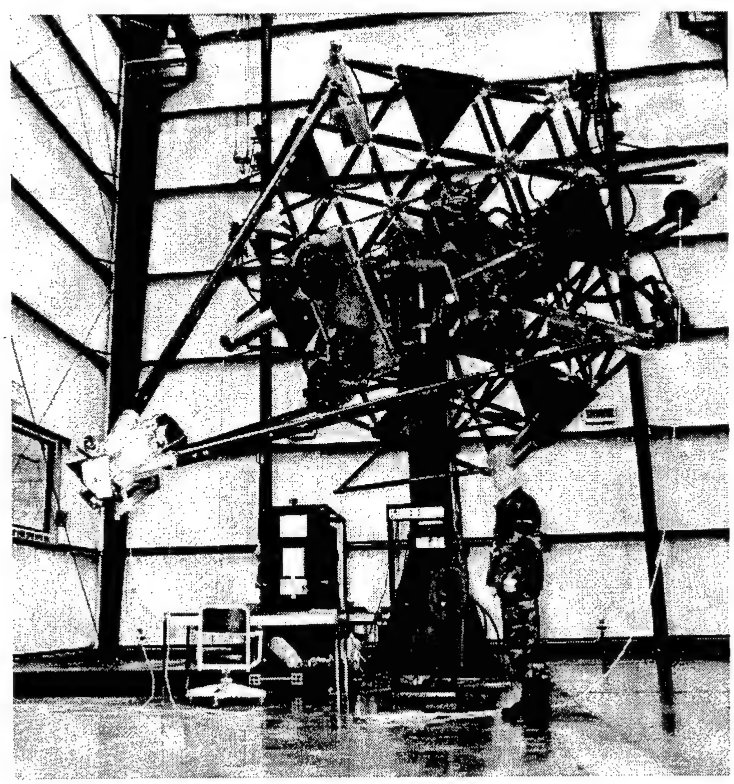

Figure III-2. The ASTREX Facility at the AFRL (Kirtland AFB) (Courtesy of AFRL)

A more important result, perhaps, was the demonstration of the scalability of the active damping concept to realistic space structures. A mission study [8] showed that active members similar to the ones employed on ASTREX could be used to settle the slew-induced vibrations of a space-based radar spacecraft in two cycles, allowing mission pointing requirements to be met. Validation testing confirmed that 100 fatigue cycles of 2,000 μ-strains and thermal cycling over the range ±100 °C had virtually no effect on the dynamic performance of active members that had a lay-up identical to the full-scale struts. Even for very large space-based structures, such as the spaced-based radar, results have shown that damping forces demanded of the active members remain in a reasonable and achievable region, in the active device linear range.

The ASTREX Facility was also used to evaluate a variety of different control approaches and algorithms. Control is a particularly important issue for spacecraft because of the difficulty of predicting on-orbit behavior (e.g., disturbances, 0-g dynamics, nonlinearities) and reliability (e.g., device failures) as shown, for example, by the March 1995 test of the NASA/Massachusetts Institute of Technology (MIT) Middeck Active Control Experiment (MACE) I on an STS-67 [33]. It is, therefore, important to have autonomous, self-adapting systems that can learn and recover from failure. One particularly successful approach tested on the ASTREX Facility involved Adaptive Neural Control, an approach developed by Harris Corporation in conjunction with AFRL. This is believed to have been the first large-scale "intelligent structure" demonstration. In this test, a multitone disturbance was controlled with no prior system knowledge. The system converged in about 7 min with a root mean square (RMS) attenuation of 27 dB across the bandwidth of interest. In another test, the structure recovered from failure of 33 percent of the actuators. The system reconverged in about 7 min with similar levels of RMS attenuation. In these tests, a Kalman filter learning algorithm was used [34]. The MACE II precision pointing experiment—involving a large team that includes the Air Force and NASA, with three universities and four industry participants—will be a shuttle flight test of these adaptive learning algorithms [35]. However, full flight validation is needed to mature this technology completely.

The ACESA program was followed by a space flight test of a tripod structure (1 ft by 1 ft by 2 ft volume) built by TRW and shown in Figure III-3. It is believed to be the first active structural experiment to be flown in space. SMAs were used to change the stiffness properties of one strut. Piezoelectric sensors and actuators embedded in the other graphite-epoxy composite struts were used to demonstrate active structural control. The

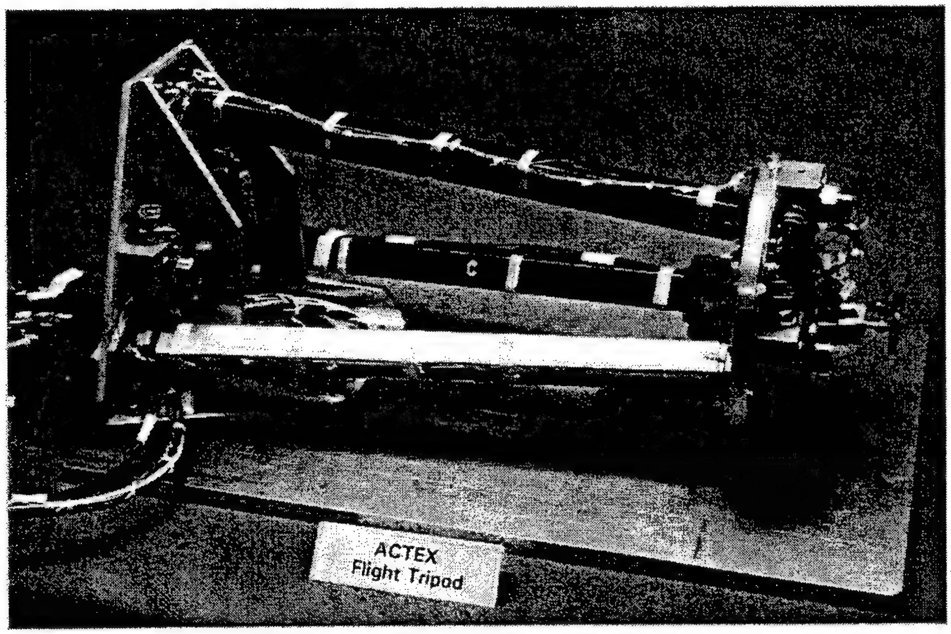

Figure III-3. Advanced Controls Technology EXperiment (ACTEX-1) Flight Hardware (Courtesy of AFRL)

Active Controls Technology EXperiment (ACTEX) has been in orbit for more than 2 years and has provided system identification and closed-loop control data over a broad range of temperatures: up to 29 dB of vibration suppression has been demonstrated (see Figure III-4) [36]. The SDIO (now BMDO) and the Air Force Phillips Laboratory (now AFRL) funded this flight experiment. The structure is currently being used for on-orbit testing of control algorithms as part of an AFRL-sponsored guest investigator program.

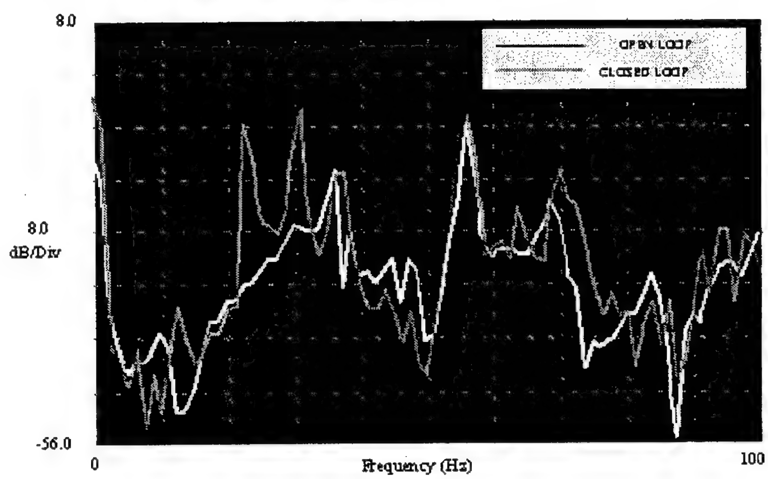

Figure III-4. ACTEX-1 Flight Test Data Showing Vibration Suppression (Courtesy of AFRL)

The objective of the follow-on ACTEX 2 experiment [37], also funded by BMDO and the Air Force, was to demonstrate improved jitter control of an active solar array yoke on an experimental space test platform. It was to be a completely autonomous experiment with flexible, programmable operation. The active yoke—containing sensors, actuators, and power and signal conductors embedded in a space-qualified, load-bearing, graphite-polycyanate composite—had adjustable structural dynamics, ultimately to provide dynamic control of the solar array over the long term while in orbit. This experimental system also had a passively damped solar array drive assembly. The key technology advancement in this experiment was the development of a modular control patch (described later), a small electronic patch integrated with the active struts in the yoke. The ACTEX II structure was successfully ground-tested but never flown.[9] This program pioneered the idea of multifunctional structural concepts.

As part of a joint program with the United Kingdom to build a small experimental satellite [Space Test Research Vehicle-2 (STRV-2)], AFRL and BMDO funded a project with Honeywell, Trisys Inc., and the Jet Propulsion Laboratory (JPL). The team designed, fabricated, and tested the Vibration Isolation and Suppression System (VISS). Its purpose was to isolate an optical system from spacecraft bus disturbances by a minimum of 20 dB at > 5 Hz; to reduce sensor motion induced by cryocooler operation by 20 dB at the first 3 harmonics of the cryocooler vibration; and to provide a limited amount of precision, fast steering (±0.30 deg). VISS, using six hybrid passive/active isolation struts in a hexapod configuration (see Figure III-5), was successfully space qualified via acoustic and random vibration testing and thermal-vacuum testing, both as a stand-alone system and as an integrated payload on the STRV-2 [38]. The satellite was launched in June 2000, and data are being collected. A future project, jointly funded by AFRL and DARPA, involves the design, fabrication, and test of a Miniature Vibration Isolation System (MVIS). The goal is a ~ 1-in^3 unit containing a piezoelectric actuator and a tunable passive element, with each unit providing 3-axis isolation.

More recent projects supported by the Air Force focus on incorporating isolation systems at the satellite/launch vehicle interface to reduce the effects of launch vibrations on spacecraft components. This is analogous to automobile suspension systems but avoids costly—and heavy—ad hoc component isolation systems. Approaches being investigated for launch isolation include linear passive systems, such as viscous dampers

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9 A flight was attempted on the first Pegasus XL launch, but the launch was aborted.

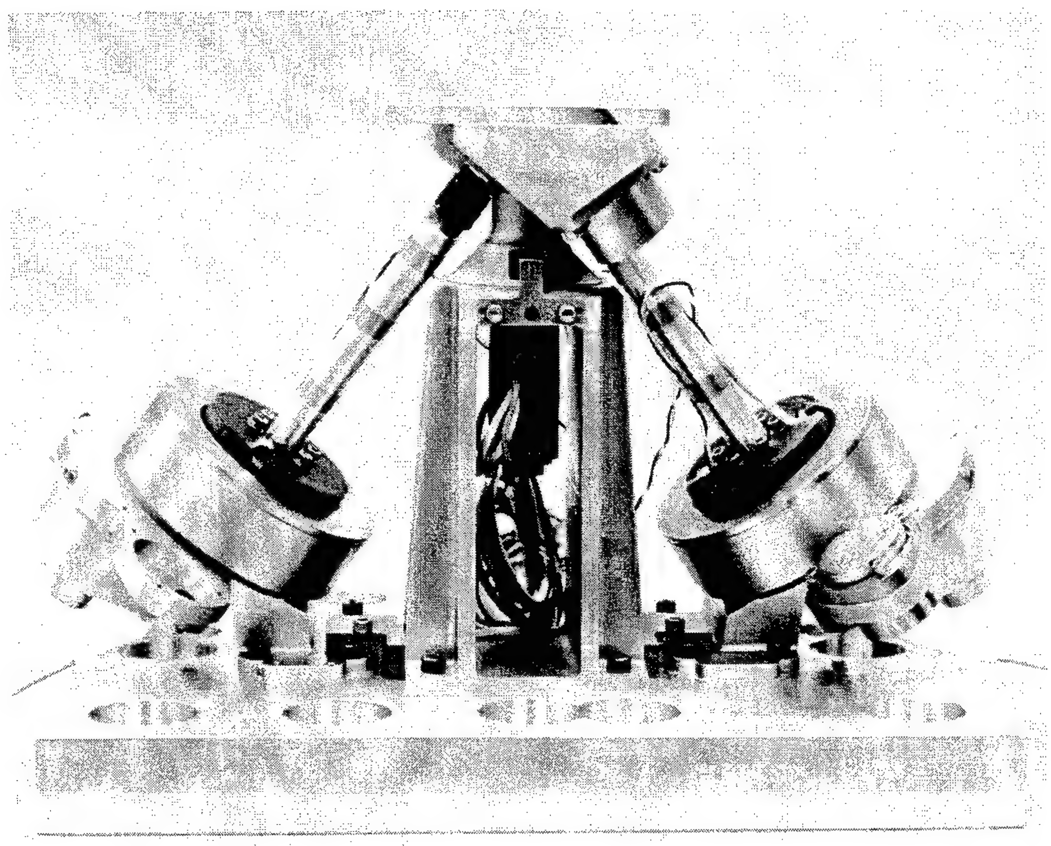

Figure III-5. VISS To Be Launched on the STRV-2
(Courtesy of Honeywell)

and viscoelastic materials, nonlinear passive systems that can achieve greater isolation with lower stroke, and hybrid systems [e.g., 39] that combine active and passive components (such as the VISS). As an example, the world's first whole spacecraft isolation system was demonstrated for the Navy Geosat Follow-on satellite, launched on a Taurus launch vehicle in February 1998. This passive system, located between the space vehicle separation ring and the launch vehicle forward cone, was designed and built by CSA Engineering under AFRL funding. It reduced critical vibrations by 86 percent, reduced overall loads by a factor of two, and saved 6 months and $8 to $10 million in redesign time and component cost [40].

The objective of acoustic satellite protection systems is to reduce the acoustic energy transmitted through the payload fairing to the satellite, a reduction that saves mass for the launch vehicle and the payload. It is a challenging problem because acoustic vibrations are broad band and high amplitude. Dynamic behavior that interferes with the launch vehicle system cannot be introduced—nor can the solution interfere with the satellite. Several new AFRL projects are addressing this problem via passive and active

techniques. Passive approaches involve innovative, simple-to-fabricate structural concepts, such as grid-stiffened structures with integrated functional capabilities. Active approaches include noise cancellation, dissipative cavity mode control, and structural control concepts. Since each of these approaches has drawbacks, a hybrid approach may ultimately be most effective. In one project, the AFRL is working with several industrial and academic partners to demonstrate a full-scale active acoustic suppression system for the Orbital/Suborbital Program (OSP) Minotaur Launch Vehicle payload fairing. This project culminates in a qualified noise reduction test of the active system. Modeling tools (e.g., integrated structural-acoustic models) are also being developed as part of this program.

Another serious vibration problem for spacecraft is attributed to shock-related failures: 83 such failures were noted in over 600 launches (up to 1984), and more than 50 percent of these 83 failures led to a catastrophic loss of mission while the remaining systems suffered from degraded performance. Examples of such failures could include broken wires and leads, dislodging of contaminants, and others, ultimately leading to component and/or subsystem failure and possibly loss of the spacecraft. Pyrotechnic release devices contribute to shock failures. These explosive devices cause large forces and accelerations, exceeding the 500-g limit at some frequencies. Solar array deployment hinges can also cause shock problems. Lockheed Martin, with funding from the AFRL, has investigated the use of SMA-based release mechanisms to reduce the shock to acceptable levels, as illustrated in Figure III-6. Example concepts include a two-stage nut (TSN) and a low-force nut (LFN) [41]. Such concepts have been flight-tested: the Shape Memory Actuation Release Devices (SMARD) experiment on the MightySat 1, an Air Force experimental satellite. MightySat was released from the shuttle STS-88 in late spring 1999. Results from the SMARD experiment showed performance levels consistent with predicted behavior for the two concepts: the TSN produced less than 200 g's of shock, the LFN produced less than 500 g's of shock, and the pyrotechnic device produced shock levels in excess of 6,000 g's [42]. The AFRL has also been working with Starsys Research, Inc. to develop second-generation devices. These SMA devices will be tested in the FalconSat Low-Shock Release experiment on OSP-1. They expect to reduce separation shock by a factor of 10 or more, to reduce the number of shock-related failures, and to demonstrate improved reliability of release mechanisms by using these devices. Since these devices are nonpyrotechnic, increased range safety and contaminant avoidance are additional benefits. A low shock, reliable SMA mechanism for solar array

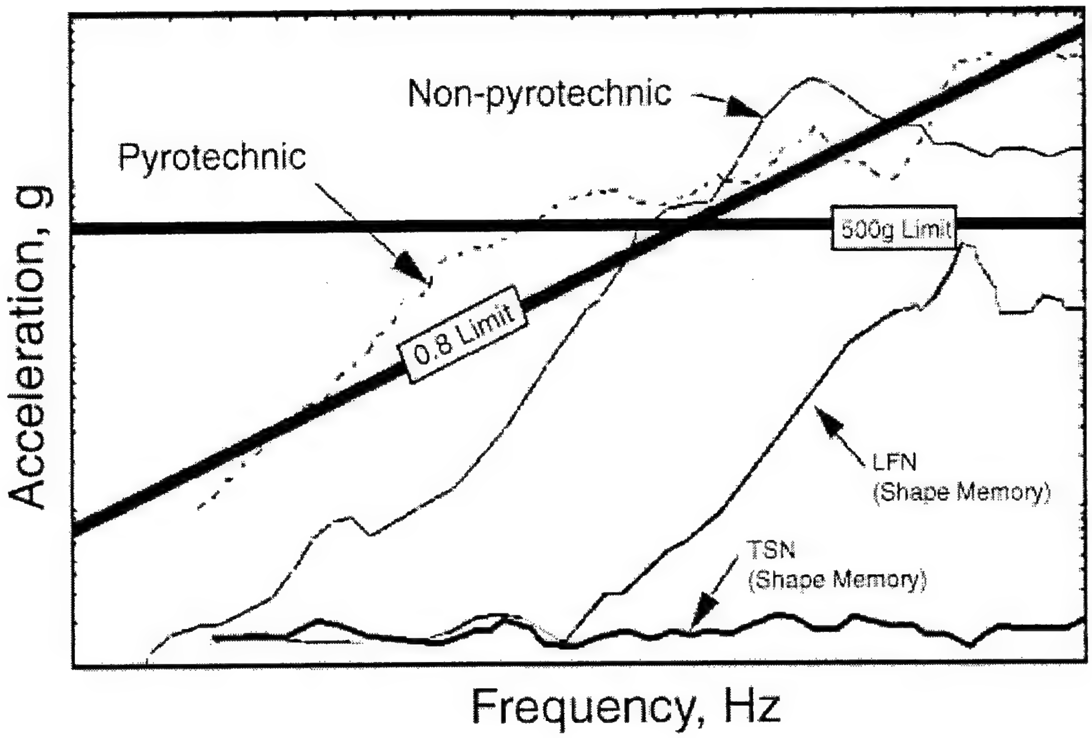

Figure III-6. Shock Vibration Design Limits for Spacecraft Compared With the Shock Vibration Performance of SMA Release Mechanisms and Conventional Pyrotechnic Devices (Courtesy of AFRL)

deployment was tested in the Lightweight Flexible Solar Array Hinge (LFSAH) experiment on STS-93 (summer 1999), sponsored by DARPA and the AFRL. Hinges are the primary mechanism used to deploy spacecraft solar arrays that are folded together for launch. Six SMA hinges were tested to verify mechanical design data and to evaluate the dynamic properties of the hinges in a realistic environment. These SMA hinges offer key advantages over other hinges: low-shock controlled deployment, fewer parts, lighter weight, higher reliability, and ease of production and assembly. Preliminary reports from the shuttle crew indicated that hinge operations were nominal. The hinges performed as expected although no data have been analyzed yet [42].

2. Air Vehicle Noise and Vibration Suppression

Active acoustic control, or the use of one acoustic source (or secondary source) to cancel another (or primary source), has a long history, particularly for air vehicles. In recent survey paper, Fuller and Von Flotow [43] described the earliest practical demonstrations of the technique and the earliest known U.S. patent. Active Structural Acoustic Control (ASAC) for air vehicle interior noise reduction is an area of particular interest to all the Services and NASA and to commercial air vehicle companies.

The most obvious difference between ASAC systems and early acoustic control systems is that ASAC uses structural actuators, such as shakers or piezoelectric (e.g., PZT) patches, attached to the aircraft fuselage rather than acoustic actuators, such as loudspeakers inside the fuselage. This concept is attractive because the structural actuators are more effective by weight and consume less interior volume than competing active or passive noise control options [44].

One important area of ASAC research involves the determination of optimal locations for actuators and sensors. Early theoretical investigations [43–47] established the importance of actuator and sensor architecture and suggested optimization strategies and goals. Much of the work focused on developing mathematical models, with some supporting experimental work to validate them. Some more recent activities have focused on developing concepts for new actuators [e.g., 48, 49] and demonstrations on real aircraft [e.g., 50–53].

Many researchers recommend a modal method for ASAC: actuators are placed to excite a selected structural mode, and sensors are placed to observe each important acoustic mode [43]. Lyle and Silcox [44] tested this modal method on a simulated aircraft fuselage and got mixed results. Although significant global interior noise reduction was obtained at a frequency at which the primary and secondary sources excited the same dominant acoustic mode, the same actuator and sensor configuration was not effective at a second frequency because a global increase in interior noise was observed. This behavior, attributed to amplification of other modes (e.g., control spill-over), could be reduced via an alternate set of actuators and sensors. While the benefits appear obvious, no practical solutions using smart technologies have been implemented on real air vehicles.

The Australian Defence Science and Technology Organization (DSTO) has conducted laboratory tests of out-of-plane vibration suppression on the tailplane of a CT-4 aircraft previously used by the Royal Australian Air Force as a basic trainer [54]. These tests used four piezoceramic (e.g., PZT) patches—two as strain sensors and two as strain actuators—to suppress out-of-plane vibrations actively. A method to find a suitable location for the sensors and actuators was developed, and a digital controller system was designed and implemented. The system significantly reduced out-of-plane vibrations and demonstrated robust characteristics.

An active aft fuselage skin panel subjected to engine noise and unsteady flow-induced vibrations has been flight-tested on the B-1B [55, 56]. This is the first known

flight test of such a system on primary aircraft structure. The system used a piezoceramic lead-lanthanate-zirconate-titanate (PLZT) patch vibration-suppression system. The primary objective was to suppress forced responses from separated flow, but the project also demonstrated that piezoelectric actuators could withstand the operational environment and loads of a real aircraft. Additional objectives of the flight test were to demonstrate fundamental and higher order mode suppression of the panel. The fuselage panel was relatively thick (0.80 in.), with a radius of curvature of approximately 38 inches. The PLZT patches were attached to the inside of the skin panel, although they may have been more effective attached to the outside. The system was designed to withstand temperatures ranging from –60 °F to 185 °F, as well as a large number of vibration cycles. A greater than 8-kHz digital processor system was designed and used to suppress the critical modes over the 400-Hz to 800-Hz range. The active control system maximized the force generated by the PLZT patches. The system was successful in reducing the fundamental panel modes by as much as 79 percent for the take-off condition and by about 46 percent for transonic flight conditions, with a 25-percent response reduction for a higher order mode.

Under another DARPA-sponsored program, Lucent Technologies applied active structural control to reducing structural vibrations in gas turbine engines [57]. They worked with Pratt & Whitney to develop solutions for particular vibration-induced problems in engine fan blades and vanes, engine cases, and external engine components. Expected benefits included improved engine durability, improved engine performance, reduced operating and support (O&S) costs, and shorter engine development cycles.

3. Buffeting Suppression

Buffeting is an aeroelastic phenomenon that plagues high-performance aircraft, especially those with twin vertical tails. Twin tail buffet arises at high angles of attack when unsteady vortices generated near the wing leading edge impinge on the tails, as shown in Figure III-7, and induce severe structural vibrations. This can lead to premature fatigue failure and more frequent inspections [58, 59]. The buffet problem is particularly severe for the F/A-18 and F-15, as evidenced by high costs associated with special 200 flight-hour inspections, repair and replacement of damaged tails, and redesign.

To reduce fatigue and thus increase the life of a vertical tail, the stresses caused by buffeting must be reduced. This reduction can be accomplished by modifying the load-carrying structure within the tail, reducing the buffet loads by altering the flowfield

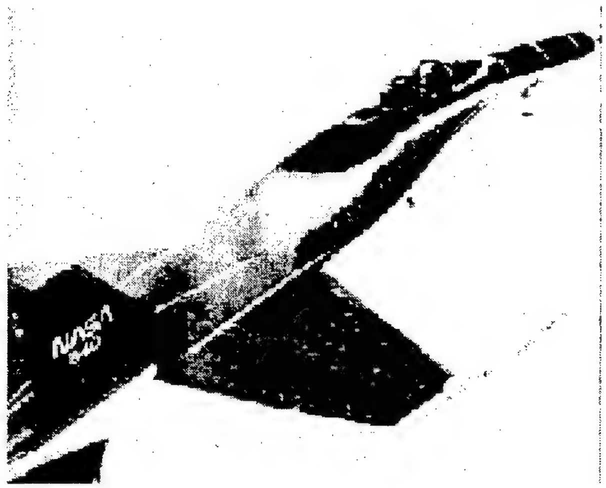

Figure III-7. An F-18 Climbing at a High Angle of Attack, With Leading Edge Vortices Impinging on the Vertical Tails

around the vertical tail, or reducing the buffeting response through active control of effectors on the tail. The success of a proposed fix to the buffeting problem has generally been measured by percentage reduction in the RMS of the strain at the root of the vertical tail.

To understand the buffeting problem, several Air Force and NASA programs have focused on quantifying the buffet loads by acquiring response measurements and surface pressures on the vertical tails of scaled models in a wind tunnel and on an actual aircraft during flight [58–65]. In general, the results of these studies are published as spectra and pressure coefficients for the inboard and outboard surface of the tail. Based on some of these studies, Boeing (formerly McDonnell Douglas) implemented an interim solution on the F-18, relying entirely upon structural modifications to the vertical tail in an attempt to reduce the dynamic stresses in critical areas [61]. However, even with the structural enhancement, the dynamic stresses were still too severe. This led to the investigation of an alternative approach that offered some improvement but also compromised the aircraft's high-alpha performance by reducing the unsteady lift and pitching moment of the aircraft [62]. Therefore, other options are being explored.

Two active approaches are being considered to address the buffeting problem. The first approach uses an actively controlled rudder. The second approach uses a smart materials and structures solution to the problem. In 1992, the concept of an actively controlled rudder was proposed to alleviate vertical tail buffeting on the F-18 and F-15 aircraft [66]. This analysis showed that an actively controlled rudder of an F-18 might be effective in adding damping to the vertical tail, resulting in reductions in the RMS of the root bending moment.

The Active Vertical Tail (AVT) project to reduce buffet response was a joint venture between McDonnell Douglas (now Boeing) and Parks College of St. Louis University [67]. The AVT was a 5 percent-scale, aeroelastically tailored structure having similar vibration response to that of a full-scale aircraft. In 1995, vertical tail buffeting alleviation was achieved using piezoelectric actuators on this double delta wing wind-tunnel model with twin vertical tails that were not canted [68]. The piezoelectric actuators were attached to the spar to control the first two bending and torsion modes. This structure was tested in a low-speed wind tunnel over angles of attack ranging from 20 to 55 deg and dynamic pressures ranging from 0.5 to 7 pounds per square foot. The peak response of the vertical tail was reduced by as much as 65 percent over the uncontrolled response. These results were achieved using simple control algorithms employing collocated strain gauges.

In 1995, the use of actively controlled piezoelectric actuators on an F/A-18 vertical tail was analyzed [69]. This analysis showed that actively controlled piezoelectric actuators might increase damping greater than 60 percent in the first bending mode, with a less than an 8-percent increase in the weight of the vertical tail.

In a NASA-Langley-sponsored program, with participation from Wright Laboratory (now AFRL) and Daimler Benz Aerospace (now DaimlerChrysler), a 1/6-scale F-18 wind-tunnel model was tested in the NASA-Langley Transonic Dynamics Tunnel (TDT) in 1995–1996, as shown in Figure III-8. This was part of the Actively Controlled Response Of Buffet-Affected Tails (ACROBAT) program to assess the use of active controls in reducing vertical tail buffeting [58, 60]. The research objectives of the ACROBAT program were twofold: to determine the spatial relationships of the differential pressures during open-loop and closed-loop conditions at various angles of attack and to apply active controls technology, using a variety of force producers, to perform buffeting alleviation on twin vertical tails of the wind-tunnel model. The starboard vertical tail was equipped with an active rudder and other aerodynamic devices, while the port vertical tail was equipped with piezoelectric actuators. By using single-input/single-output control laws, the power spectral density of the root strains at the frequency of the first bending mode of the vertical tail was reduced by as much as 60 percent for angles of attack up to 37 deg. RMS values of root strain were reduced by as much as 19 percent. The ACROBAT program results demonstrated that buffeting alleviation of the vertical tails on an F-18 could be achieved using active piezoelectric actuators or rudder articulation [60]. This investigation was the first known experimental

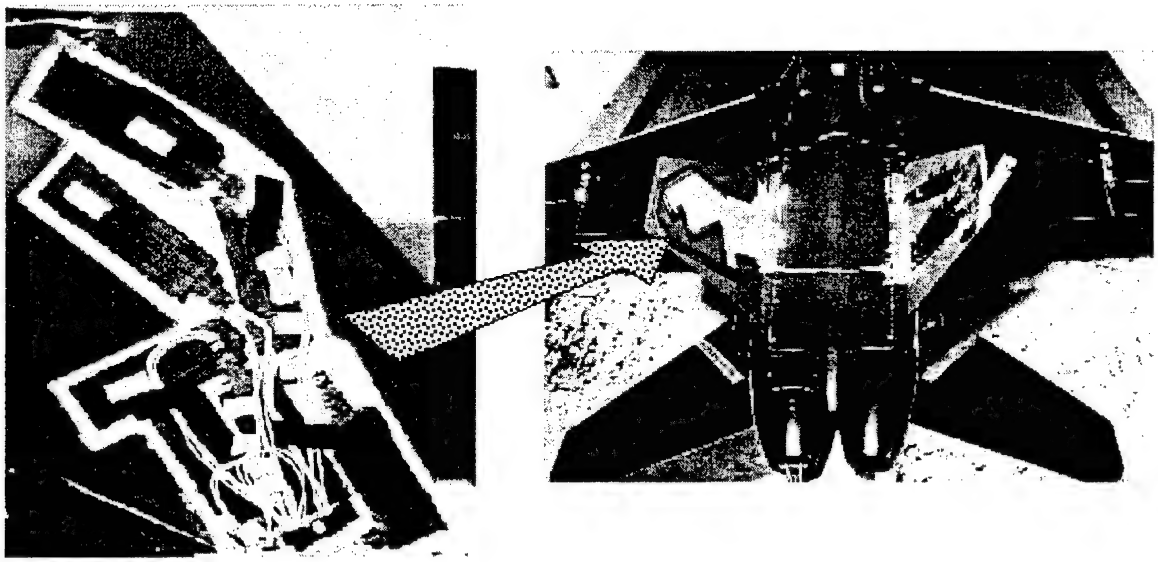

Figure III-8. A 1/6-Scale F-18 Model Mounted in the NASA-Langley TDT During the ACROBAT Program (Courtesy of NASA-Langley)

demonstration of active buffeting alleviation on a scaled F-18 wind-tunnel model using an active rudder and piezoelectric actuators.

Ground tests of an active buffet suppression system were conducted on a full-scale F/A-18 in Australia under the auspices of The Technical Cooperation Program (TTCP) program [59, 70, 71]. These tests were completed in February 1998 at the Aeronautics and Maritime Research Laboratory (AMRL) in Melbourne, Australia, using the International Follow-On Structural Testing Project (IFOSTP) rig (see Figure III-9). The test facility used air bags and shakers to simulate buffet loads on the aircraft. Patch piezoelectric actuators produced by Active Controls eXperts (ACX), Inc., were surface-bonded to the starboard vertical fin. ACX also designed and built the control system. Four different simulated flight conditions, as shown in Figure III-10, were evaluated in the tests. To maximize control authority for each simulated flight condition, ACX designed and tested a separate optimal controller for each of the four flight conditions. Figure III-10 also shows the results in percent reduction of RMS bending moment. The buffet alleviation targets were not quite achieved in these experiments because the non-linear effects of the shaker load on the modal response had not been considered in the mathematical model of the plant. Also contributing to the results is the fact that, during the worst-case flight condition, only one control law functioned over the entire duration of the load cycle without overdriving the amplifiers. Overdriving the amplifiers caused shutdown of the affected piezo-system so that it was no longer active in reducing root bending moment.

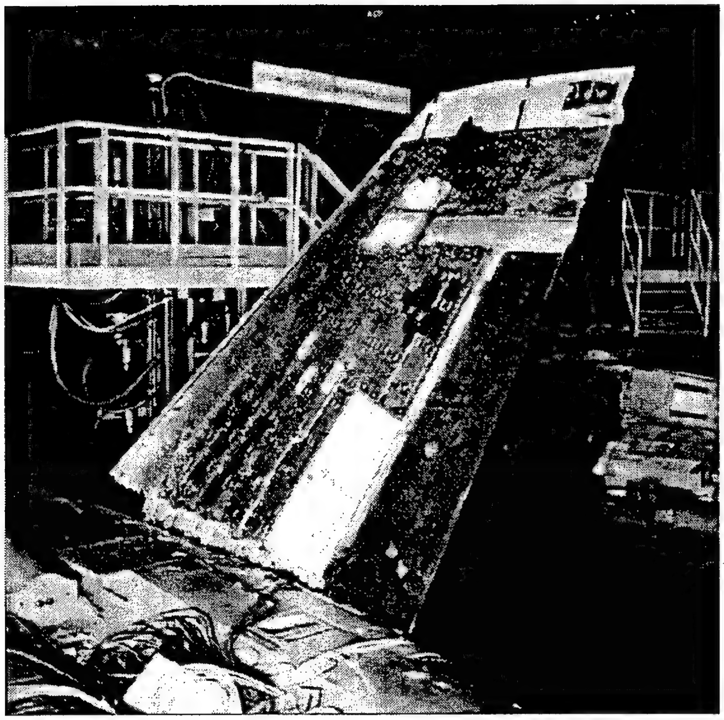

Figure III-9. Full-Scale Ground Test of an Active Buffet Suppression System (Courtesy of ACX, Inc., and AMRL, Australia)

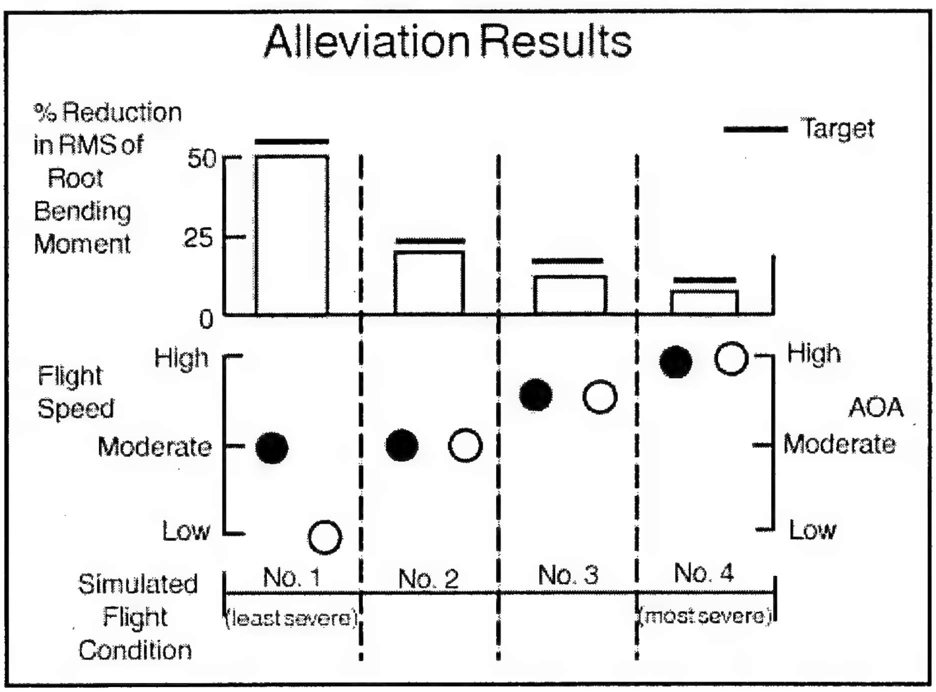

Figure III-10. Flight Conditions and Simulated Buffet Alleviation Results in Percent Reduction in RMS Bending Moment Achieved Using the Piezoelectric Actuators During the Full-Scale Ground Test (Courtesy of NASA-Langley)

The Air Force has sponsored other projects addressing buffet load alleviation. Rohini International examined stacked piezoelectric actuators to solve this problem. Since stacked piezoceramic actuators provide only uniaxial motion, an assembly was designed to transform the longitudinal motion into moments that would provide the control actuation. The Rohini system was demonstrated in ground and wind-tunnel tests. A 1/16th-scale F-15 model was tested in the Subsonic Aerodynamic Research Laboratory facility at AFRL and in the Research Institute Model Test Facility at Georgia Institute of Technology [72]. Some of the experiments performed during this study included four different angles of attack (14 deg, 17 deg, 20 deg, and 23 deg) at free stream dynamic pressures that varied from 5 to 13 pounds per square foot. The results showed that the system was effective over the entire buffet domain. As the disturbance increased, however, the effectiveness of the control decreased.

An interagency study currently underway will down-select the most effective buffet load alleviation approach for a planned follow-on effort. A flight demonstration program is scheduled for years 2001 to 2003.

Similar, ongoing efforts in Europe are also focused on the application of smart structures technologies to the buffet problem [e.g., 73–79].

4. Flutter Suppression

The interaction of structural dynamics with the aerodynamic characteristics of an air vehicle at particular flight conditions causes flutter—a series of divergent and destructive oscillating motions. It is a safety-of-flight concern. In fighter aircraft, flutter is aggravated by the presence of under-wing weapons [80]. Solutions generally involve increasing structural stiffness, mass balancing, or modifying geometry, all of which typically increase weight and cost while decreasing system performance.

A cooperative project between NASA-Langley and MIT—the Piezoelectric Aeroelastic Response Tailoring Investigation (PARTI)—focused on the wing flutter problem [e.g., 81–83]. The PARTI experiments, which took place from 1991 to 1996, were analytical and experimental studies based on a relatively large, multi-degree-of-freedom aeroelastic testbed. Program objectives were to demonstrate the ability of strain-actuated adaptive wings to control aeroelastic phenomena, including wing flutter suppression and gust load alleviation, and to develop experimental and analytical techniques. To accomplish these objectives, a wind-tunnel model was designed and fabricated, aeroservoelastic analyses were performed, and the model was ground and wind-tunnel tested in NASA Langley's TDT [84].

The existing PARTI wind-tunnel model, shown in Figure III-11, consists of a composite plate in a sandwich construction (graphite fiber-reinforced epoxy facesheets with an aluminum honeycomb core) with piezoelectric patches surface-bonded to each side of the plate. Conventional strain gages and accelerometers are also included. The piezoelectric patches are arranged into 15 groups to be used either as 15 actuators or sensors or a combination of both. During this program, active flutter suppression and reduced gust loads using piezoelectric actuation were successfully demonstrated in wind-tunnel testing of the 4-foot long semi-span wing model: flutter dynamic pressure was increased 12 percent and wing root bending moment caused by gust was reduced by 75 percent. Although the model tested during the PARTI program was a plate-like model (vs. a conventional monocoque structure), the experimental results provided evidence that piezoelectric technology may offer a viable alternative to conventional aeroelastic control techniques.

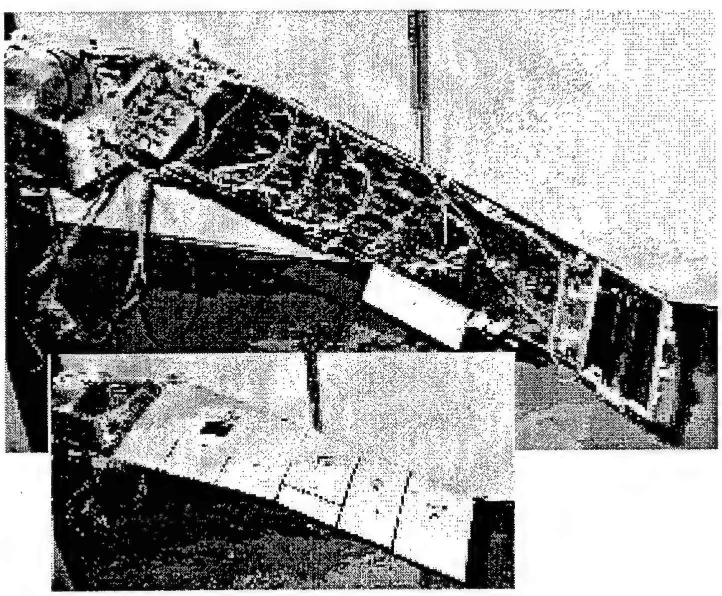

Figure III-11. The PARTI Wind-Tunnel Model (Courtesy of NASA-Langley)

Because of the PARTI program, an extensive database of experimental information was gathered and is being used to help understand the many issues associated with applying strain actuation technology to dynamic problems. Three key issues identified during the PARTI program have provided guidance to NASA in establishing research focus areas and related follow-on activities:

- Development of detailed structural and aeroelastic models to promote a better understanding of the local and global effects of piezoelectric actuation[10]
- Investigation of piezoelectric power consumption characteristics during active control to enable a realistic evaluation of the economic viability of using piezoelectric actuators on full-scale vehicles[11]
- Development of improved control and optimization techniques to use the piezoelectric capabilities to their fullest extent.[12]

5. Rotorcraft Vibration Suppression

The aerodynamics of rotating blades are quite complex. The aerodynamic environment varies with blade position around the azimuth and leads to sub-optimal performance throughout much of the flight envelope. One particular issue, BVI noise, is caused by the wake from the previous helicopter blade meeting the leading edge of the next blade.

Vibrations increase when blades are out of track. Blade-tracking adjustments, required to account for slight physical differences between the helicopter blades, are done infrequently because of the high cost, significant set-up time, and subsequent maintenance. Active, real-time blade tracking adjustments can produce large savings in maintenance costs and have an additional feature important in military operations: downtime for tracking adjustments can be significantly reduced.

Boeing Defense and Space Group formed a DARPA-supported consortium—Smart Structures for Rotorcraft Control (SSRC)—involving the Boeing Helicopter Division (Philadelphia), MIT, Pennsylvania State University (PSU), and Analytic Engineering. This team addressed control of trailing edge flaps and trim tabs as well as active twist control of helicopter rotor blades in the Phase I program. Expected performance improvements included an 80- to 90-percent reduction in vibrations, 5 to 10 dB reduction in BVI noise, blade twist of ±2 deg, and trailing edge flap motion of ±3 deg, all to be achieved without compromising the required safety levels. The designs

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10 Finite element and aeroservoelastic modeling and validation research are both underway to address this issue.

11 Ground tests are being conducted to investigate the efficiency of active and passive control schemes. These tests use a method for predicting the power consumption of piezoelectric actuators that was developed in a follow-on study to the PARTI program.

12 To date, two studies have used data from the PARTI wind-tunnel tests to examine optimal control using the piezoelectric actuators, and further research is planned in this area using the PARTI model for open- and closed-loop ground tests.

and performance benefits were based on an existing CH-47 Chinook blade design. Actuation schemes under consideration included a discrete piezoelectric actuator for flap motion, SMA torsional actuators for trim tab motion, and a distributed, InterDigitated Electrode–Piezoelectric Fiber Composite (IDE–PFC) or Active Fiber Composite (AFC) actuator for blade twist. The SMA actuator was bench-tested, and the two piezoelectric concepts were spin-tested on model CH-47 blades. Preliminary experiments to evaluate integrity of the embedded piezoceramics and to characterize their performance under loading conditions (especially fatigue) were completed. One 1/16 Froude-scale CH-47 blade was fabricated using the IDE–PFC and bench-tested to evaluate twist actuation performance: a maximum twist of 1.4 deg was measured (at 2,000 V) under static conditions [85]. This AFC concept will be described in more detail later. Issues associated with any integrated devices included actuator ability to handle the large centrifugal loads, drag associated with external actuator elements, and harsh operational environments.

The McDonnell Douglas Helicopter (now Boeing Helicopter in Mesa) Phase I demonstration—Smart Materials Actuated Rotor Technology (SMART) program (also supported by DARPA)—considered active control of a rotor blade trailing edge flap and trailing edge trim tab [86]. Expected performance improvements for the flap included a 10 dB reduction in BVI noise while landing, an 80-percent reduction in airframe vibrations, a 10-percent gain in rotor performance (lift/drag), and improved maneuverability from stall alleviation. For the trim tab, the goal was to eliminate manual tracking requirements, relax blade manufacturing tolerances, and reduce vibrations. The designs and performance benefits were based on an existing MD-900 Explorer system (see Figure III-12), a twin engine, 6,000-pound helicopter with a 34-foot, all-composite main rotor. Phase I actuator concepts for the flap included a multilayer, co-fired electrostrictive stack with a pre-load mechanism and a stroke amplification flexure. Two torsional SMA tubes with a locking mechanism (to hold the tab in place so that power was not continually required) were considered for the tab actuator device. Integration issues included actuator ability to handle centrifugal force loading, mass balance in the chordwise direction, actuator reliability and durability, actuator size for blade geometry constraints and aerodynamic profile considerations, and blade structural integrity with the integrated devices [86]. Risk reduction tests included characterization of actuator materials, actuator bench and spin tests, and integrated system tests.

Figure III-12. The MD-900 Helicopter (Courtesy of Boeing-Mesa)

Both of these helicopter projects were combined in the DARPA Phase II effort and are managed by Boeing in Philadelphia. Boeing is currently developing a full-scale MD-900 active flap rotor, using smart materials to achieve reduced vibrations, noise, and improved performance as noted for the Phase I program. Trailing edge flaps, extending from 74- to 92-percent blade span, will be actuated by mechanically amplified piezo-electric actuators installed inside the blade spar (see Figure III-13). This active flap will provide the modification of aerodynamic forces required to affect helicopter perform-ance. The University of California at Los Angeles (UCLA) has characterized properties[13] of several stacked piezoceramic actuators under electrical, mechanical, and combined electro-mechanical loading conditions to determine their durability [87, 88]. Results of this work will be used to determine the most suitable and reliable candidate that can meet the requirements for the active trailing edge device. Several device concepts have been bench-tested in Boeing-Mesa's laboratory to evaluate basic performance. Important device characteristics included stroke, force, bandwidth, power consumption, and thermal behavior. Stiffness, damping, and inertia were adjusted to simulate a range of mechanical loading conditions on the actuator devices. For additional testing, the bench test rig and

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13 Both static and fatigue properties were evaluated. Directly measured properties include strain output, permittivity, mechanical stiffness, energy density, and coupling coefficients as a function of mechanical loading parameters and electric field values. Effects of temperature and mechanical pre-load on stack properties during ferroelectric fatigue (up to 10^7 cycles) are also under investigation.

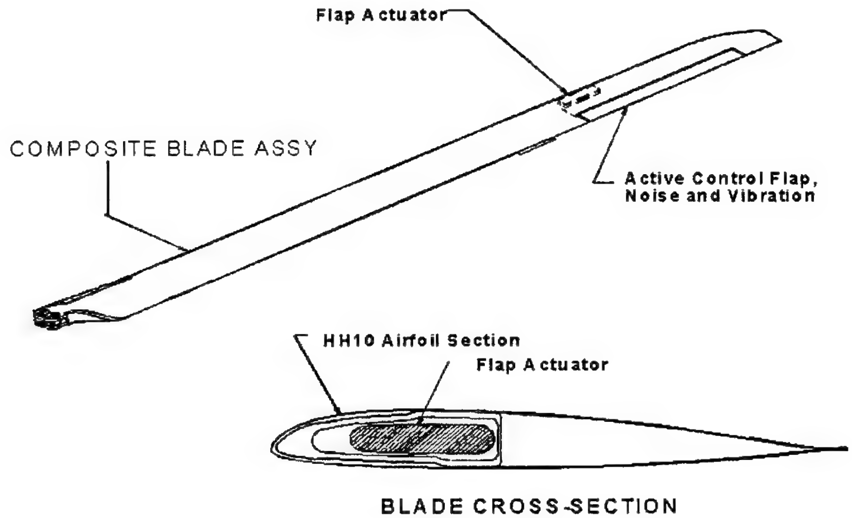

Figure III-13. The Layout of the MD-900 Smart Helicopter Blade (Courtesy of Boeing-Mesa)

actuator were mounted on a shaker table or in a centrifuge to evaluate actuator performance under simulated rotor blade vibratory motions and centrifugal force loading. A unique X-frame actuator concept [89–91], developed by MIT and shown in Figure III-14, has been selected for the final demonstration articles. Table III-1 lists some of the model-scale properties of the X-frame actuator. Preliminary blade production has been initiated and is expected to be completed by December 2000. The full-scale, 5-bladed MD-900 rotor is expected to be whirl-tower-tested in February 2001 and flight-tested in late spring of 2001.

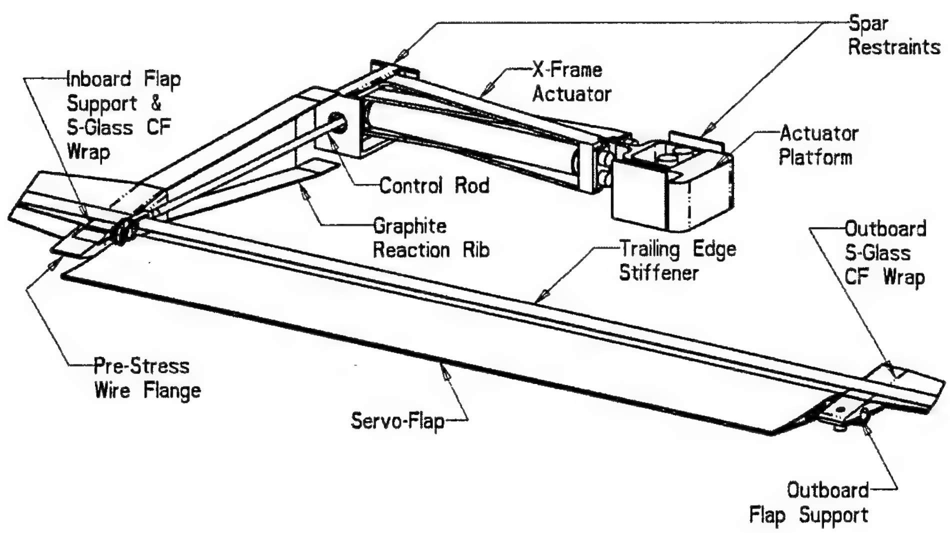

Figure III-14. Schematic of the X-Frame Actuator Integrated With the Trailing Edge Flap (Courtesy of MIT)

Table III-1. Model Scale Properties of the MIT X-Frame Actuator

Property	Value
Peak-to-Peak Free Stroke	0.056 inches
Peak-to-Peak Blocked Force	20.7 lbf
Tip Stiffness	370 lbf/inch
Bandwidth*	660 Hz
Weight	0.086 lbm

* Driving a nearly impedance matched load.

The AFC research at MIT is being pursued on a parallel path to this Phase II flight demonstration task. A major focus of this parallel task is to demonstrate the benefits of an active twist rotor system via a test of a Mach-scale rotor, complete with predictions and extrapolation to a full-scale rotor. Recent analytical and experimental investigations [86, 92–96] suggest that helicopter rotor blades containing embedded AFCs may be capable of meeting the performance requirements necessary for a practical individual blade control (IBC) system [97]. An IBC system would allow the elimination of the swashplate, swashplate actuators, rotor blade torque tubes, and lag dampers. This would be a very significant step forward for improving helicopter performance. For example, an 85-percent range increase is predicted by combining advanced rotor technologies with on-blade flight control for a UH-60 baseline system [98].

Defining what is meant by the term, "Active Fiber Composite," is important before proceeding further. AFCs consist of piezoelectric fibers embedded in an epoxy matrix with other inactive reinforcements to improve the durability characteristics of the actuator [99, 100]. An interdigitated electrode poling method [101] is used to generate large directional actuation strains in the actuator plane. Combining both of these technologies results in a piezoelectric actuator laminate with induced stress, endurance, and conformability characteristics superior to typical monolithic piezoceramic actuators.[14] In the AFC rotor blade concept, AFC plies are oriented at ±45 deg within the primary structure of the blade to generate dynamic blade twisting. Analytical studies indicate that twist amplitudes of 1 to 2 deg over a relatively wide frequency bandwidth are possible using the strain actuation capabilities of the AFC plies. System studies also indicate that this magnitude of twist actuation authority should be possible at full scale,

[14] Of no small significance is the fact that ultimate realization of this actuator concept will require the development of manufacturing technology and an industrial base for the production of piezoelectric fibers and composite laminates. DARPA has sponsored a project with Mide Corporation, Continuum Control Corporation, and CeraNova Corporation to address these needs.

with only modest increases in blade weight and, possibly, relatively low levels of power consumption.

Additional focus areas for this DARPA task include prequalifying the AFC design for full-scale demonstration (via detailed design and analyses) and studying system integration issues. Shortly after the Phase II task was initiated, a Mach-scale blade, shown in Figure III-15, was spin-tested. Although the test was successful, it highlighted several issues, all of which affected the measured performance: voids, delaminations, AFC pack failures, and electrical connection failures, caused in large part, by the AFC and blade manufacturing processes. Ongoing tasks have addressed these issues. The final demonstration in this task is expected to be a hover test of a Mach-scale rotor in December 2000.

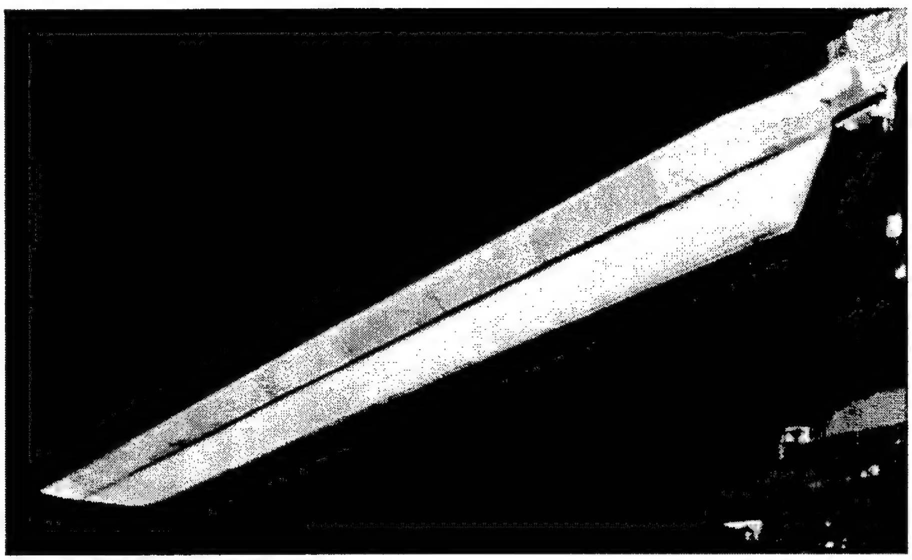

Figure III-15. Mach-Scale AFC Blade Spin-Tested at MIT (Courtesy of MIT)

In another DARPA-sponsored program, Lucent Technologies and Sikorsky Aircraft have addressed two helicopter problems: reducing rotor blade noise via active rotor control and cutting vibration and noise levels in helicopter cabins via active control of noise and vibrations carried through transmission mounts [57]. The project was concerned with both low (e.g., from the rotor blades) and high (1 kHz from the transmission system) frequencies. Approaches considered in the tradeoff studies included blade root control, blade twist, blade flaps, and other active airfoil concepts. Technical issues identified were similar to those identified in the Boeing programs. Plans included

designing and fabricating a model active rotor control system, which was to be tested at Sikorsky rotor test facilities and in an acoustic wind tunnel.[15]

Concurrent with these DARPA programs are several closely related Army- and NASA-sponsored efforts. These programs are focused on similar activities but generally at a more fundamental level. Examples include active circulation and trailing edge flap or tab control [e.g., 102–104], active suspension for adaptive vibration isolation, active blade twist control, active fuselage walls for vibration damping and noise reduction, and active vibration control in a 20-mm gun.

Active twist concepts are of special interest for the reasons previously identified. One program in particular—a cooperative effort between NASA, the Army Research Laboratory (ARL), and MIT—focuses on the AFCs also being investigated in the DARPA Phase II effort. As part of this joint effort, an aeroelastically scaled, actively twisted, rotor research model is being fabricated for testing in the heavy gas environment of the NASA-Langley TDT. The test section of the TDT in Figure III-16 shows the Aeroelastic Rotor Experimental System (ARES) [105], which will be used to operate the active twist rotor model. These wind-tunnel tests will serve as an important demonstration of the active twist rotor concept and will provide valuable experimental data for validation of active twist rotor analytical tools.

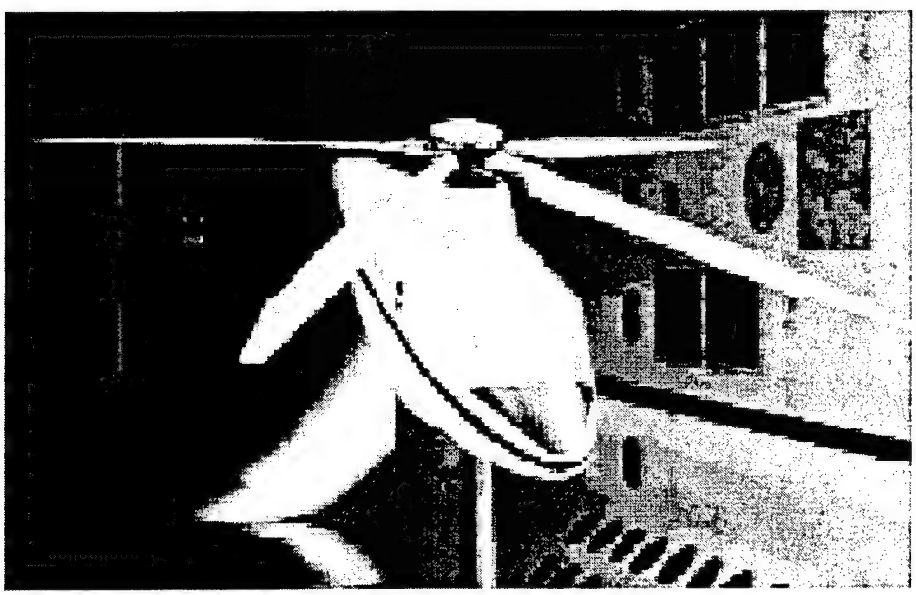

Figure III-16. The ARES 9-ft Diameter Rotor Testbed in the NASA-Langley TDT (Courtesy of NASA-Langley)

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15 The program ended before conclusive results could be obtained.

These activities are expected to form the foundation of future advanced active twist rotor research efforts for the Army and NASA. This Future Technology Rotor (FTR) will incorporate advanced airfoils, planform geometry, and active twist capability in an optimized, integrated, intelligent rotor blade structure. By considering active twist capabilities from the beginning of the rotor design process, it should be possible to create an advanced rotor with aerodynamic performance, vibratory loads, and acoustic characteristics much superior to those obtainable with purely passive rotor blade structure designs.

C. SHAPE ADAPTIVE STRUCTURES

The concept of shape adaptive structures and aerodynamic flow control figures predominantly in current thinking regarding applications for smart materials and structures technologies. Design concepts of interest include wing warping, camber shaping/control surface deformation, and variable stiffness structures (see Figure III-17), among others. Specific objectives in the shape adaptive structures area are developing innovative design processes, eliminating discrete control surfaces, and enhancing maneuver performance. Among the expected performance benefits are reduced signature and drag and increased take-off gross weight and range capabilities.

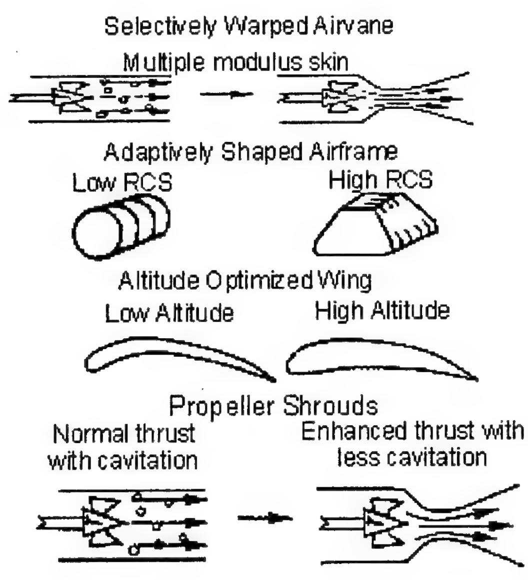

Figure III-17. Concepts for Shape Adaptive Structures (Courtesy of AFRL)

Several small systems have been built and tested since the early 1990s to demonstrate that shape adaptive structures are possible and that flight control through the use of smart materials and structures is feasible and can offer significant performance

advantages for a variety of systems [106]. The very earliest demonstrator used directionally attached piezoelectric actuators to achieve twist in a subsonic National Advisory Committee on Aeronautics (NACA) 0012 aircraft wing. Other systems included a supersonic variation of the subsonic active twist wing [107] and an active torque-plate concept for a NACA 0010 missile fin [108]. Later demonstrations along these lines (in the mid-to-late 1990s) focused on flight control for small vehicles, such as fixed-wing aircraft [109], helicopters [110], barrel-launched munitions [111], and micro-air vehicles (MAVs) [106]. These demonstrations are the first known applications of smart technologies for air vehicle control surfaces. Other programs concurrent with these have pursued active shape control concepts for larger systems.

Two DARPA programs, the Smart Wing program and the Smart Aircraft and Marine Propulsion System demONstration (SAMPSON) program, are particularly concerned with shape adaptive structures for aircraft. Other groups, including the DLR[16] (Germany) [112], Air Force, and NASA, are also working on such structures for aircraft.

1. Aircraft Wings

Benefits of active control of wing shape have been demonstrated and well documented [e.g., 14–16]. As an illustration, consider the use of conventional vs. continuous control surfaces (see Figure III-18). Deployment of conventional control surfaces can, in effect, change the overall wing camber; however, these same rigid surfaces give rise to discontinuous boundaries, which, in turn, result in early air flow separation and, ultimately, reduced lift and increased drag. Use of smoothly contoured control surfaces, however, delays flow separation and improves lift and stall angle characteristics.

Techniques for wing twist and camber control using smart structures approaches are being developed under the DARPA Smart Wing program [e.g., 113, 114]. Northrop Grumman was awarded contracts for Phase I (September 1994) and Phase II (August 1998). Other members of the large team of researchers involved in the program have included Lockheed Martin Astronautics, Lockheed Martin Control Systems, Naval Research Laboratory (NRL), Mission Research Corporation, Rockwell Science Center, Fiber & Sensor Technologies, Etrema Products, SRI International, UCLA, Georgia

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[16] DLR (Deutsche Forschungsanstalt für Luft und Raumfahrt) is Germany's national aerospace research center.

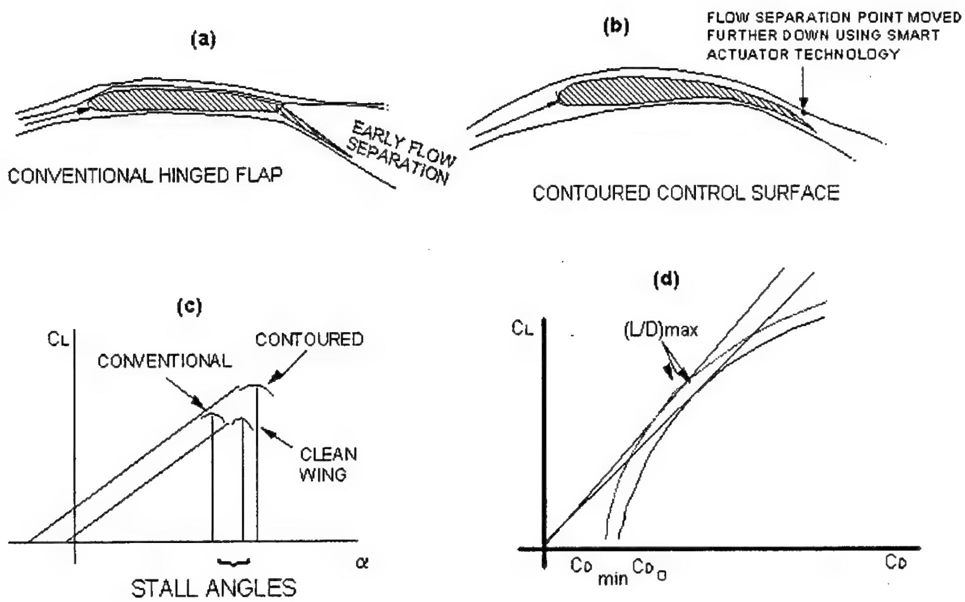

Figure III-18. Schematic Illustrating the Benefits of Continuous vs. Conventional Control Surfaces (Courtesy of Northrop Grumman)

Institute of Technology, and the University of Texas at Arlington. NASA-Langley's TDT provides wind-tunnel testing for the program [84]. The AFRL currently manages the program.

The overall objective of this program is to design, develop, and demonstrate the use of smart materials and structures to improve the aerodynamic performance of military aircraft, including improvements in lift-to-drag (L/D) ratio, maneuver capabilities, and aeroelastic effects [114, 115]. Estimated performance improvements for fighter aircraft include an 8-percent increase in allowable take-off gross weight, a 30-percent increase in weapons payload, and a 10- to 15-percent increase in maneuver rates. The approach includes designing, fabricating, and testing scaled semi-span and full-span wind-tunnel models; addressing power, reliability, packaging, and system integration issues; and laying the ground work for technology transition in a potential follow-on program.

During Phase I of the program, a 16-percent scaled semi-span model of the F/A-18 aircraft was designed and fabricated, incorporating three key features: hingeless, smoothly contoured, trailing edge control surfaces; variable spanwise wing twist; and fiber-optic strain and pressure transducers [114]. On this model, the hingeless aileron and flap were actuated using SMA tendons as shown in Figure III-19 [e.g., 114, 116]. For the first tunnel entry on the smart model, wing twist was accomplished by using two SMA-actuated torque tubes. Only one torque tube was used in the second wind-tunnel

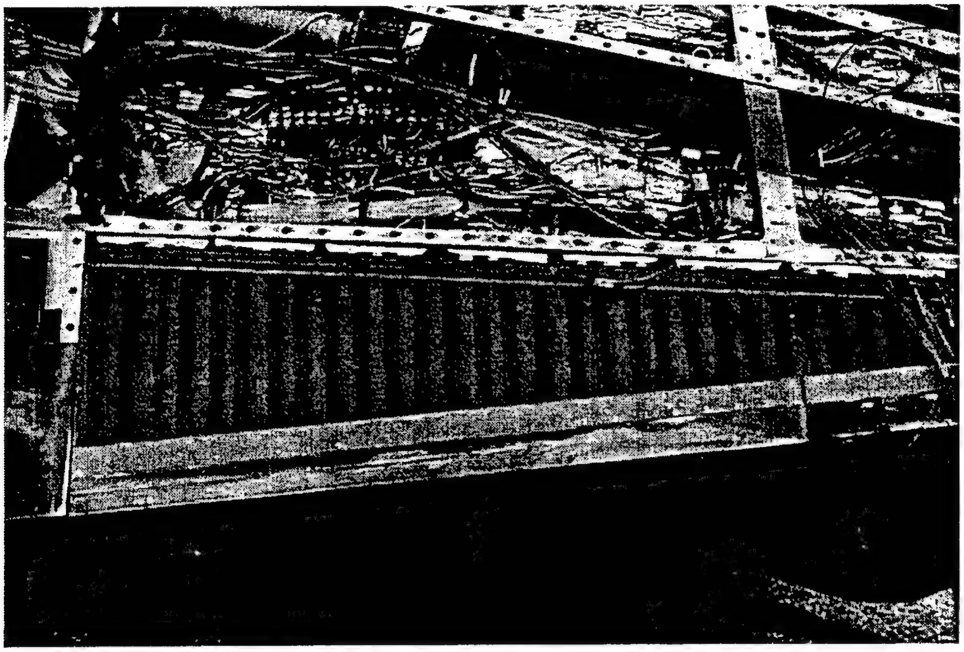

Figure III-19. Control Surface Hardware for the First Smart Wing Wind-Tunnel Entry (Courtesy of Northrop Grumman)

test (see Table III-2 for a more detailed comparison [114, 116, 117]). Figure III-20 shows a layout of the smart wing. Fiber-optic pressure and strain sensors were included in the first wind-tunnel test. The strain sensors were used as part of the feedback, and the specially developed pressure sensors were shown to be highly accurate. Another identically scaled model of conventional construction—hinged control surfaces and no wing twist—was fabricated and used as a baseline for comparison. This model was used in both wind-tunnel tests.

Table III-2. Comparison of Smart Wing SMA Torque Tube Actuators

Wind-Tunnel Test 1	Wind-Tunnel Test 2
Two SMA torque tubes: Inboard 1-in. diameter, 1,200 in.-lb torque Outboard 0.5-in. diameter 600 in.-lb torque	One SMA torque tube: 1.125-in. diameter 0.060-in. wall thickness 3,600 in.-lb torque
Nichrome wire heater	Nichrome wire heater
1.25-deg spanwise twist (measured)	4.5-deg spanwise twist (measured)

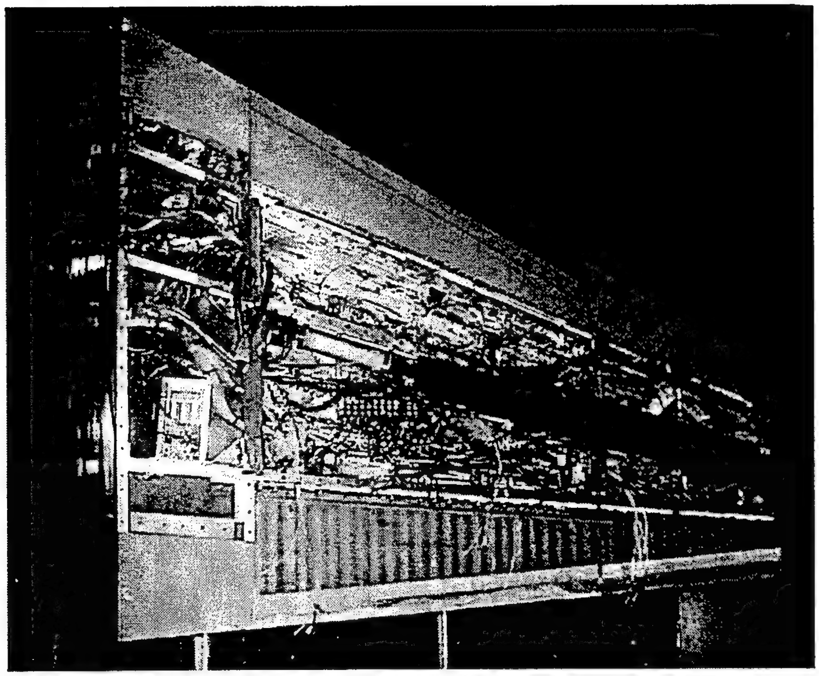

Figure III-20. Layout of the Smart Wing (Courtesy of Northrop Grumman)

The first Phase I wind-tunnel test took place in May 1996. Figure III-21 shows a photograph of the Smart Wing model in the TDT. During this test, 1.25 deg of twist was achieved using the SMA torque tubes, resulting in approximately an 8-percent improvement in rolling moment. The hingeless control surfaces deployed up to 10 deg and provided between an 8- and 18-percent increase in rolling moment and approximately an 8-percent increase in lift [118].

The second Phase I wind-tunnel test in took place in June–July 1998. In this test, the Smart Wing contained a single, redesigned torque tube and hingeless control surfaces similar to those used in the first test. During this test, 5 deg of twist was achieved, resulting in a 15-percent increase in rolling moment. In addition, deflections of up to 10 deg on the hingeless control surfaces were obtained with improved controllability and repeatability. Table III-3 summarizes important results from both tests [114, 119].

The actuator scale-up results shown in Table III-4 were an important conclusion from the Phase I tests. Analyses indicate that torque requirements for a full-size fighter aircraft wing are so large that they are beyond the capability of present-day actuation materials, even with innovative actuator designs.[17]

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[17] Note that this conclusion assumes current aircraft structural design methodologies are used. For innovative design approaches based on very flexible structures, for example, this may not be the case.

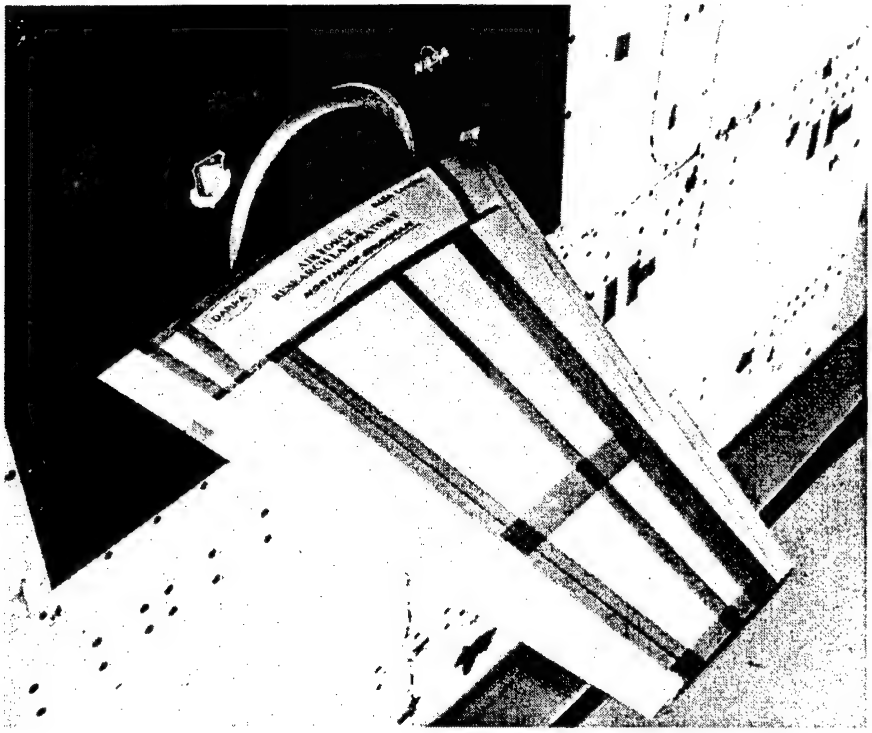


Figure III-21. The Smart Wing Phase I Model in the NASA-Langley TDT (Courtesy of Northrop Grumman)

Table III-3. Summary of Performance Improvements for Smart Wing Angle of Attack = 8 deg

Configuration	Deflection or Wing Twist (deg)	Lift ΔC_L	Roll ΔC_L	Lift and Roll % Improvements: Lift	Lift and Roll % Improvements: Roll
Flap Only[1]	7.5	0.058	0.019	9.7	10.2
Combined Flap Aileron[1]	7.5	0.092	0.039	17.6	17.1
Aileron Only[1]	5		0.015		8.0
Aileron Only[2]	10		0.019		10.5
Wing Twist[2]	3 5	0.034 0.05	0.019 0.03	8.0 11.5	10.0 15.6
Wing Twist[1]	1.4	0.041	0.022	10.0	12.8
Combined Aileron and Wing Twist	+10-deg Aileron +4.5-deg Wing Twist	0.057	0.031	15.3	17.3

[1] Wind-tunnel test 1.

[2] Wind-tunnel test 2.

Table III-4. Derived Torque and Rotation Requirements for a Shape Adaptive Wing

Component	Full-Scale Aircraft (Torque)	16% Model (Torque)	20% Model (Torque)	Rotation (deg)
Wing Box Twist				
@ 50% span	2.000×10^6	1.5×10^3	3.0×10^3	2
@ Wing tip	0.160×10^6	3.0×10^2	6.0×10^2	5
Leading Edge Flap				
Inboard	0.185×10^6	1.3×10^3	2.5×10^3	10
Outboard	0.250×10^6	0.5×10^3	9.3×10^2	10
Trailing Edge Flap				
Inboard	0.160×10^6	8.8×10^2	1.7×10^3	10
Outboard	0.032×10^6	3.1×10^2	6.0×10^2	10

Note for Table III-4: All torques are in inch-pounds.

Another Phase I Smart Wing task examined approaches to allow subtle changes in wing cross section to reduce transonic drag. At the speeds where most transport aircraft fly (just under Mach 1), air flowing over the wing can be supersonic in some locations and subsonic in others. When the airflow changes abruptly between those regions, a shock wave forms over the wing. The objective of this task was to provide a capability for shockless transonic cruise by subtly changing the airfoil shape at various stages of the flight profile, thus allowing up to 75 percent reduced drag, as well as reduced fuel consumption. The concept involved a truss-like system of magnetostrictive actuators, designed to fit a full-scale Gulfstream III wing [120]. This system was not tested because analysis indicated that the added weight of the actuation system would effectively cancel the benefits expected from reshaping the airfoil. This analysis also led to the conclusion that improved lightweight actuators are required to realize the benefits of real-time, active airfoil shape optimization. It was determined that the same benefits could be realized by suitably deploying two flaps with built-in actuators (e.g., like Fowler flaps) rather than by changing the entire wing cross section.

A key limitation in the Phase I effort was the low bandwidth of the control surfaces. The SMA actuation system performed at a fraction of a hertz. Even with improvements in materials technology and active cooling concepts, the system would not be able to provide the tens of hertz response required for operational aircraft. Phase II of the Smart Wing program includes plans to mature further the technologies developed in Phase I and to investigate new actuation concepts (e.g., hybrid piezoelectric devices and piezoelectric motors) to address the bandwidth limitations. The structure of choice is a

30-percent scale Unmanned Combat Air Vehicle (UCAV) design. The full-span model[18] has a 10-foot wing span with a 12-foot length and weighs close to 500 pounds (see Figure III-22). It is fully instrumented to measure strains, pressure, force, deflection, and acceleration. Expected performance benefits for this type of vehicle using these "Smart Wing" technologies include reduced turn radius, increased range, improved survivability, and increased sorties. Data from the first wind-tunnel tests in air and heavy gas in the NASA-Langley TDT, completed in March 2000, are currently being analyzed. A second wind-tunnel test, tentatively planned for February 2001, will focus specifically on the actuator bandwidth issue.

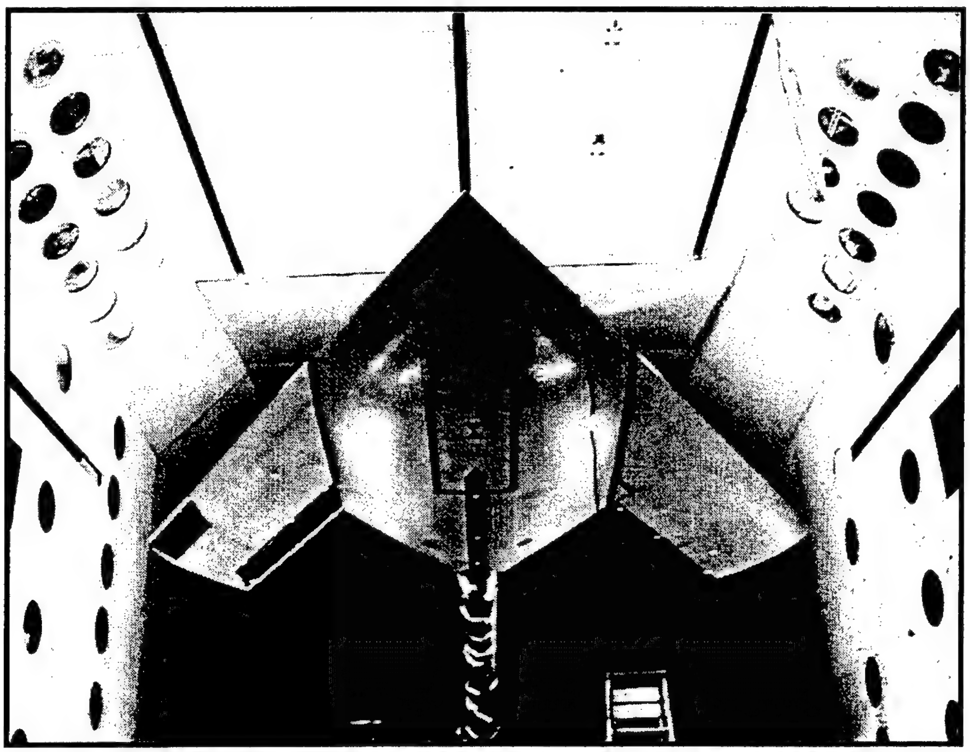


Figure III-22. The Smart Wing Phase II Model in the NASA-Langley TDT (Courtesy of Northrop Grumman)

Air Force efforts in shape adaptive structures are focused on enhancing vehicle performance by eliminating discrete control surfaces and structural dynamic problems on current and future aircraft. Some of the Air Force demonstration activities have been conducted in conjunction with NASA. The Active Aeroelastic Wing (AAW) (also called Active Flexible Wing) is a more complex project involving vehicle structure, controls,

18 The conventional half of the model uses electric motor-driven flaps and ailerons while the smart half uses SMA-activated leading and trailing edges. Note that the smart control surfaces can be smoothly varied in both the chordwise and spanwise directions, a first test of this capability.

and aerodynamics to maximize performance [e.g., 121–123]. This multidisciplinary effort takes advantage of inherent aeroelastic flexibility in the wing, with the leading and trailing edge control surfaces being used as aerodynamic tabs. The airstream twists the wing with minimal deflections of the control surfaces, and surfaces can be optimized as a set for most efficient control under all flight conditions. This technique is expected to be flight-tested. Expected benefits for this AAW technology generally include substantially increased control power, reduced drag and aircraft structural weight, and increased design latitude for wing span, sweep, and depth. Combining variable stiffness mechanisms with this concept may reduce the size and power of the control surfaces and actuation systems presently being used in the AAW, as well as the weight, by as much as 30 percent, depending on the aircraft configuration and mission profile. Variable stiffness devices may also result in improved stealth characteristics and cruise efficiency and reduced drag, attractive in both manned and unmanned vehicles.

2. Engine Inlets

The inlet system of jet-powered aircraft preconditions the air entering the engine. Jet engines require air to enter the engine at approximately Mach 0.5 or less. Because of the wide range of Mach speeds, altitude, angle-of-attack, angle-of-slip, and engine airflow conditions, a fixed geometry inlet cannot provide ideal performance under all conditions. At low speeds, large inlets with very blunt lips are desirable. This allows the high airflow associated with take-off conditions to be drawn into the inlet without flow separation. At subsonic cruise, sharp inlet lips are desirable because they produce less drag. Sharp inlets also reduce RCS. At supersonic conditions, the losses caused by rapidly decelerating the flow from supersonic to subsonic result in substantial losses in pressure and thrust. To overcome these limitations, variable geometry inlets have been used. The variable geometry inlets used on the F-15, for example, improve performance over a range of conditions, but their mechanical complexity adds weight and cost to the aircraft. Compliant mechanisms using smart materials and structures technology for variable leading and trailing edges are thought to be a simpler alternative to implement. These are flexible structures that change shape by deformation rather than by conventional rigid body motions.

Smart materials and structures technologies have advanced to the point where it is now feasible to demonstrate such physical shape control. The DARPA-sponsored SAMPSON program involves Boeing-St. Louis (formerly McDonnell Douglas) with the following team members: Lockheed Martin Astronautics, Georgia Institute of

Technology, NRL, Electric Boat Corporation, BBN (now GTE), and PSU's Applied Research Laboratory (ARL) and Center for Acoustics and Vibration. This program is managed jointly by NASA-Langley and ONR and is focused on both aircraft and submarine applications, with a specific interest in shape and flow control approaches for inlets (see Figure III-23). Wind-tunnel testing of the full-scale aircraft inlet will be performed at NASA-Langley facilities.

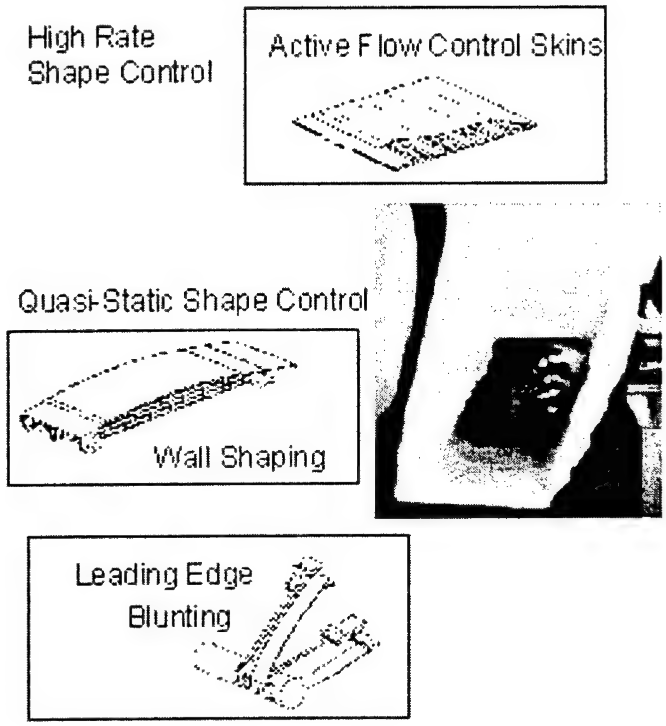
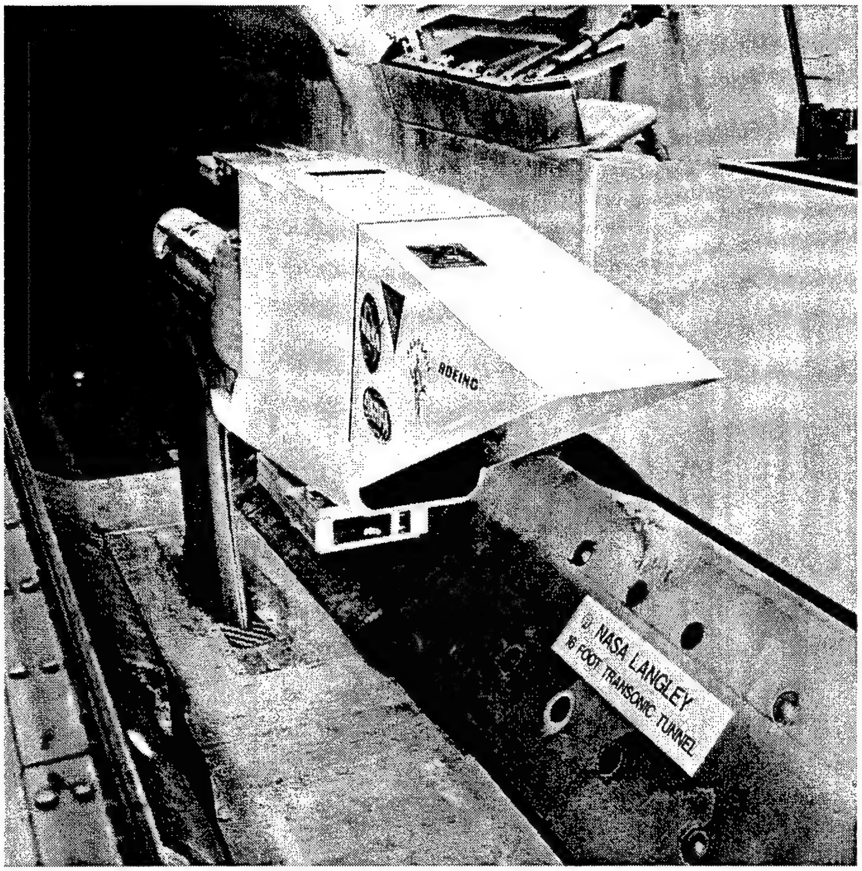
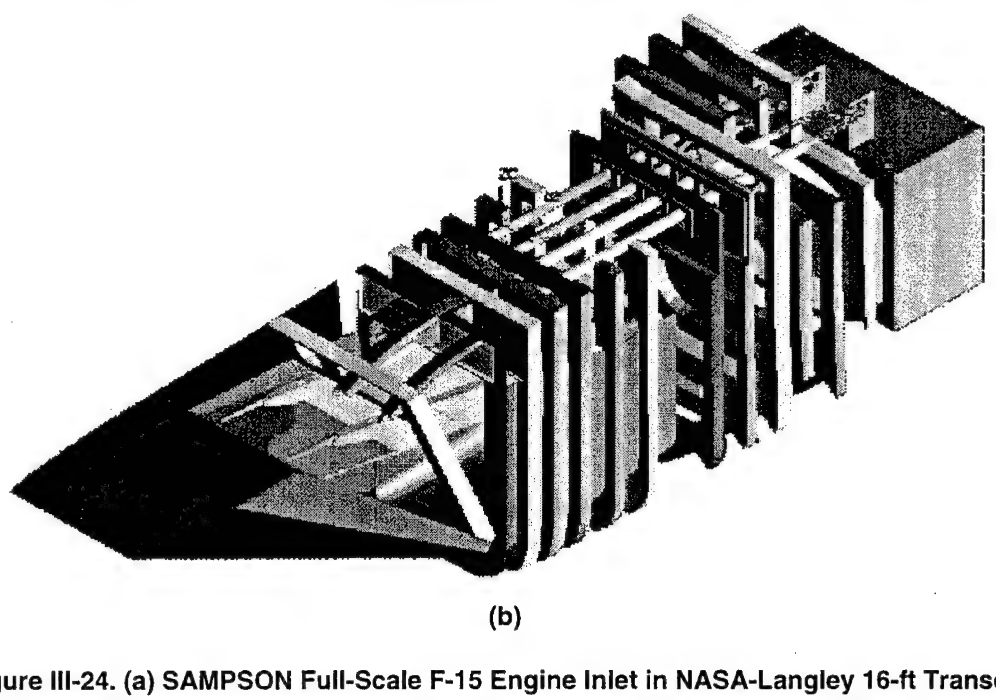


Figure III-23. Concepts for the Shape Adaptive Inlet Demonstration in the SAMPSON Program (Courtesy of Boeing Phantom Works)

Objectives for the aircraft portion of SAMPSON include designing, fabricating, and demonstrating a full-scale adaptive inlet for a tactical F-15 Eagle aircraft (see Figure III-24a), with a particular focus on validating control of inlet geometry and internal flows [124]. Potential benefits include improved range (20 percent for tactical aircraft) and maneuverability, flutter and buffet control, and reduced signature. Important core technology efforts are addressing needs for quasi-static shape control for inlet shaping, leading edge lip deflection, and leading edge blunting via compliant surfaces actuated with SMAs. Piezoelectric motor concepts are being evaluated for high-rate motion of the leading edge lip for blunting. As part of this wind-tunnel test program, an actuator system based on SMAs will be used to rotate the cowl about a pivot point to vary capture area (see Figure III-24b), similar to the way the current inlet operates. The forces



(a)



(b)

Figure III-24. (a) SAMPSON Full-Scale F-15 Engine Inlet in NASA-Langley 16-ft Transonic Tunnel (Courtesy of Boeing Phantom Works and NASA-Langley); (b) Schematic Showing Arrangement of SMA Tendon Actuators in Inlet Cowl (Courtesy of Boeing Phantom Works)

to achieve the necessary stroke (about 6 in.) are quite large, on the order of 20,000 lb. The advantage of using SMAs in this way is their integration into the structure, which eliminates the need for a separate subsystem (e.g., hydraulics) to run it. Bench tests of some of the SMA actuator devices have been completed, and these devices were integrated into subcomponents and tested in 1999. The first wind-tunnel test of the full-scale section was completed in April 2000, and data are currently being analyzed to determine performance benefits. This first test is expected to establish test procedures, verify aerodynamic loads, and demonstrate cowl actuation. A second wind-tunnel test is planned for November 2000. The cowl actuation concept will be refined and other concepts will be demonstrated in this test.

Active flow control skins using synthetic jets to alter the boundary layer (for compression ramp generation) were also considered in the early SAMPSON studies. Preliminary wind-tunnel tests showed promising results, but this concept will not be part of the final demonstration article. Boeing has a related program with NASA-Langley and Georgia Tech for an Integrated MEMS Flight Maneuvering System. The objectives of this effort are to develop and test an integrated synthetic jet flight control module using micro-machined fluidic drivers and multifunctional composite structure design and manufacturing. NASA-Langley also has a cooperative effort with Lockheed Martin on innovative control effector design issues using distributed fluidic drivers and their effect on aircraft control [125]. All of these programs leverage the others.

3. Missile Fins

Modern, fast maneuvering, guided missiles require highly dynamic fin actuation with excellent feedback control. Strong aerodynamic loads act on the control surfaces of a missile in flight. Up to 2,000 pounds of force can be applied to the fin. Therefore, it requires a great deal of power—up to 1 kW per fin shaft—to actuate the fin to produce rapid maneuvers in the missile. Barrett used directionally attached piezoelectric (DAP) torque-plates to pitch a missile fin statically to (4.5 deg and dynamically at rates in excess of 30 Hz [126]. Barrett has also shown that adaptive materials could be used to generate fin pitch deflections useful for missile flight control with the proper force and bandwidth capability [127]. LFK GmbH[19] is conducting research in the use of smart materials to develop new actuators for application to missiles [128]. This work is examining the use

[19] LFK-Lenkflugkörpersysteme GmbH (LFK GmbH) is a subsidiary of the European Aeronautic Defence and Space Company (EADS).

of magnetostrictive alloys, piezoelectric ceramics, and SMAs in various actuator configurations.

D. INTEGRATED ELECTRONICS

Military air vehicles typically contain large numbers of antennas that protrude from the surface. For example, the F-18 has 66 antenna apertures located at 37 sites. These apertures cover a broad range of frequency bands—from megahertz to gigahertz levels—for radar and communications functions. These externally mounted antennas require local reinforcement of the structure to accommodate electromagnetic windows, a feature that adds weight and cost. Nonconformal antennas degrade vehicle aerodynamic performance, require substantial maintenance, and increase vehicle signature. The military Services desire to minimize the number of antenna sites by combining functional capabilities of the different devices at fewer sites while still maintaining equivalent or better coverage. Some believe that up to 50 percent of the vehicle's surface could be used to exploit this capability [129]. Controllable, reconfigurable antennas or conformal antennas are probably required to achieve the desired mission flexibility. Potential benefits include reduced weight and volume, low observability (especially for conformal antennas), reduced energy consumption, improved system performance (including flexible capabilities to enable new missions), and lower costs because of reduced duplication and potentially easier repair and maintenance.

All the military Services are interested in technologies that result in low observability. Specific approaches that allow a smooth surface shape to be maintained are, therefore, desirable. As in all the smart structures applications identified previously, the miniaturization of processing and control electronics will be one step toward achieving this goal. The Air Force supported a demonstration program at Northrop Grumman—Smart Skin Structures Technology Demonstration (S^3TD)—to address some of these problems. A key feature of this program is the development of Conformal Load-Bearing Antenna Structures (CLAS), wherein the antenna element and associated structure carry the structural loads, obviating the need for heavy local reinforcements and eliminating structural cutouts. Analyses indicate that many requirements can be met with a single broad band element, but selected narrow band elements are necessary to achieve the right gain levels as well as for special functions [e.g., Global Positioning System (GPS)]. Expected performance benefits include:

- An entirely new electronic warfare (EW) capability for tactical fighter aircraft at very low frequencies (e.g., for threat identification, threat angle of arrival, and situational assessment)
- The potential for higher EW frequency bands using the same materials and processing techniques
- Significant LO performance at relatively low cost
- Reduced drag and improved range
- Enhanced low frequency performance for voice communications.

Secondary benefits include reduced weight and ease of manufacturing because of eliminated fasteners and doublers, reduced structural cutouts[20] [130], and reduced costs. The Air Force predicts a cost savings of about $250,000 per airframe, with a weight savings of about 70 pounds for the F-22. More optimistic projections estimate cost savings ranging from $0.5 million to $3.3 million per aircraft and weight savings ranging from 260 to 1,000 pounds per aircraft [130].

Future smart skin efforts will look at improved avionics and, eventually, completely integrated antennas and avionics (load-bearing) combined with adaptive structures, vibration suppression, and structural integrity monitoring capabilities.

Northrop Grumman, TRW, and PSU have designed and fabricated a full-scale, load-bearing antenna to be embedded in typical fighter fuselage skin structure (a hypothetical F-18 for a next-generation mission) [e.g., 131]. Several subscale panels were evaluated for their structural and electrical performance and manufacturability. Figure III-25a shows antenna components for the final demonstration article. The final demonstration article in this program was a full-scale, curved panel (about 3 ft by 3 ft) that was tested under combined axial and shear loads for both static and fatigue loading conditions (see Figure III-25b). The panel withstood 4,000 lb/in. of running load (equivalent to 148,000 lb total load) [130], and a 4,700 μstrain was achieved. The panel survived a fatigue lifetime and ultimately failed at 150 percent of its design limit load. Experimental data agreed well with the predicted responses.

Northrop Grumman has also investigated conformal antenna installation in the vertical tail of a military aircraft [132]. Their analyses indicated that communication link

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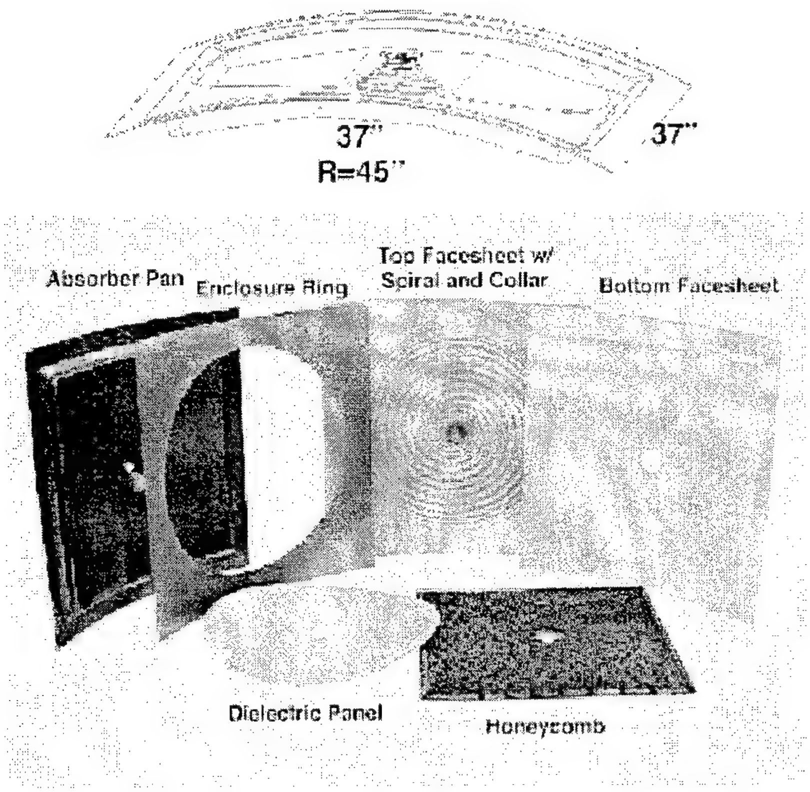
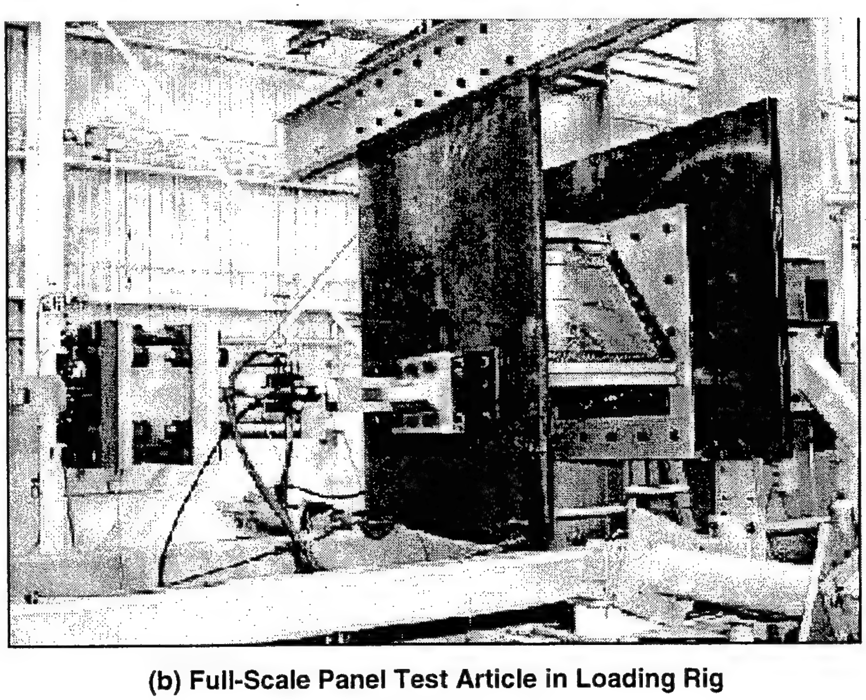
20 Up to a 75-percent reduction in structural cutouts is thought possible.



(a) Antenna Components



(b) Full-Scale Panel Test Article in Loading Rig

Figure III-25. Integrated Antenna/Structure (Courtesy of Northrop Grumman)

ranges[21] could be significantly improved by such installation. Gain improvements of up to 25 dB were demonstrated in flight tests on the NASA-Dryden Systems Research Aircraft (SRA) F-18 flight test bed. Structural integration considerations were significant because of the large number of items already located there. Tail buffet and flutter were also considered in the design. Material concerns, which included moisture absorption and acoustic fatigue of the candidate structural foam core, were addressed by environmental and fatigue testing. Material and device susceptibility to lightning damage remains an issue. The resin transfer molding (RTM) process was used for fabrication, primarily for reasons of cost, to produce the vertical tail end cap. Both of these Northrop Grumman projects were constrained, to some degree, by the requirement to use existing avionics/electronics. With advanced avionics, even greater benefits can be realized.

As another example, the Joint Attack Strike Technology (now the JSF) program funded design studies and limited demonstration work at Northrop Grumman (formerly Westinghouse) and Raytheon (formerly Hughes) for multifunctional RF systems [133], the goal being lighter weight and lower life-cycle cost relative to current systems. These systems included multifunctional nose array antennas, support electronics, appropriate application software, and sensor/resource management control. The nose arrays can be used for air-to-ground and air-to-air radar functions, for traditional radar electronic warfare, and for communications, navigation, and identification (CNI).

Other programs on integrated electronics focus on spacecraft systems. A jointly sponsored (Air Force, BMDO, and DARPA) program—the Spacecraft Integrated Electronic Structure (SIES)—addressed the weight issue by embedding power distribution and data transmission lines into structural skins [37]. General program objectives included reducing weight and volume by eliminating brackets and connectors and incorporating bulky cables into the composite skin, as shown in Figure III-26a. Electronics enclosure and harness weight reductions of 70 percent were predicted.[22] Lockheed Martin-Denver has addressed issues associated with panel-to-panel connections and multi-chip module (MCM) attachment to (and removal from) the skin. A multifunctional structural panel was flight-tested on the Deep Space-1 (DS-1) comet/asteroid fly-by mission (launched October 1998), part of NASA's New Millennium Program (NMP) [134, 135]. This panel, shown in Figure III-26b, included the following components:

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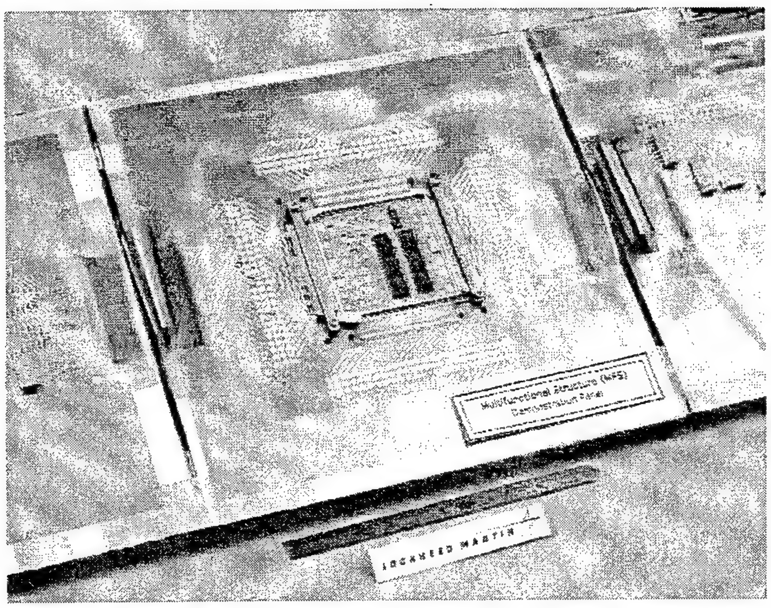
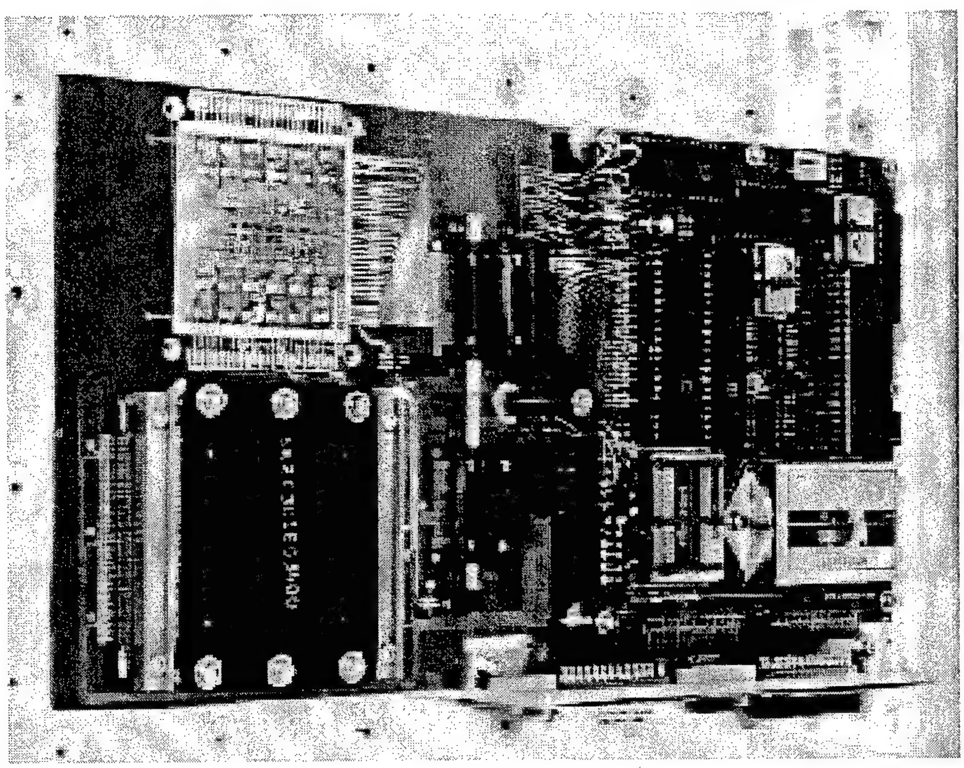
21 Bands of interest include VHF–FM (30 to 88 MHz), VHF–AM (108 to 156 MHz), and UHF (225 to 400 MHz).

22 These items typically represent about 68 percent of the total weight of a small spacecraft.



(a) Development Panel



(b) Flight-Hardware-Tested on the DS-1 Mission in 1998

Figure III-26. SIES Panels (Courtesy of Lockheed Martin Astronautics)

a micro-controller printed circuit board for the spacecraft data collection interface, a high/low power distribution MCM, a thermal simulator MCM, and a radiation-hardened

composite cover. Several key technology elements were demonstrated: embedded electronics interconnnect system using flexible circuitry, MCMs and MCM socketing, flexible circuit jumpers, anisotropic electrical bonding, temperature sensors, and thermal doublers—all on a spacecraft structural panel. In this experiment, electrical-interconnect continuity tests were successfully performed. In addition, measures of thermal performance were consistent with predicted levels. Data are still being downloaded at regular intervals. This structural concept will also be evaluated in other space flight tests, including the New Millennium Program (NMP) Deep Space-2 (DS-2), STRV-1d, MightySat II.1 (Sindri), and the Advanced Technology Demonstration Spacecraft (ATDS).

ITN Energy Systems is developing several other integrated multifunctional system concepts in which structural, power supply, and electronic functions are combined [136]. The lithium battery core (LiBaCore) honeycomb structure (see Figure III-27) uses large area roll-to-roll lithium batteries as the honeycomb material sandwiched between a face sheet containing a photovoltaic material on the one side and a face sheet with flex-circuit electronics on the other side. This multifunctional material is envisioned as the structural material for fabrication of high-altitude, long-duration unmanned air vehicles (UAVs) and micro-spacecraft. The ITN multifunctional concepts extend to integrated structure/electronics/power packs for use in habitable spacecraft and space-based radar (SBR) systems.

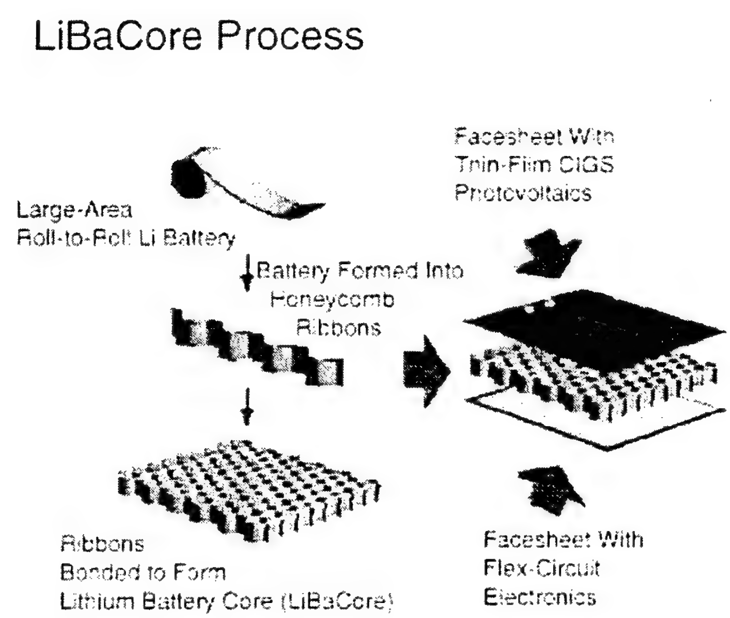


Figure III-27. Schematic of the LiBaCore Honeycomb Structure Being Developed by ITN (Courtesy of ITN)

IV. TECHNOLOGY STATUS AND ISSUES

While some elements of smart materials and structures technology are being demonstrated in current programs, many technical issues still need to be addressed before production air and space vehicles will be realized. Table IV-1 outlines the categories of important issues to be resolved before smart materials and structures technologies will likely be deployed in real air and space applications. The multidisciplinary nature of smart materials and structures makes it difficult to discuss relevant technologies and technical issues independent of one another. However, the important technical elements and their associated issues are generally ascribed to the following categories: materials, devices (sensors, actuators, and electronics), analytical methods (theories and design tools, including controls), and systems integration.

Universities, government and national laboratories, and industry are addressing many of the specific concerns in ongoing, mostly government-supported research programs. Some groups have taken an integrated, multidisciplinary approach to address technical issues associated with applying these technologies in real systems. For example, the Aircraft Morphing Program at NASA-Langley is attempting to couple research activities across a wide range of disciplines— including structures, flow physics, acoustics, controls, integration, and systems and multidisciplinary optimization—to demonstrate the required technologies to achieve significant system benefits [e.g., 137].

This part of the paper describes the current status of these critical supporting elements[22] and addresses limitations preventing real applications in production systems.

A. MATERIALS

The term "smart materials" has been applied to a broad range of materials that have one or more physical properties that can be varied with some input. By using these materials, a device that once consisted of separate structural, sensing, and actuation

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22 The body of literature related to these technical areas is quite large, on the order of many hundreds of papers per year. At best, the authors can provide an introduction to the issues and identify a few references as starting points.

Table IV-1. Smart Materials and Structures Issues

MATERIALS

- Optimization of figures of merit of materials with respect to composition and processing
- Forms of the materials
- Characterization

DEVICES

- Sensors
  - Robustness
  - Prediction of their affect on the structure
- Actuators
  - Displacement and force capability of smart actuators
  - Power consumption
  - Response time
  - Prediction of their affect on the structure
  - Robustness
- Electronics
  - Power supplies with the necessary high voltage, high current, and high bandwidth
  - Packaging of power electronics and the actuator system for minimum volume/weight
  - Information management and control

ANALYTICAL METHODS

- Theories
  - Nonlinear and micro mechanics theories
  - Theories describing cross-coupling phenomena
  - Control theories capable of handling very large numbers of actuators and sensors
- Design Tools
  - Material and structure response simulators
  - Models describing material and component interface behavior
  - Control system simulators

SYSTEMS INTEGRATION

- Availability of materials and components
- Manufacturability
- Characterization of collective behavior
  - Strength
  - Fatigue
  - Durability
  - Reliability
  - Calibration
- Efficiency
- Repairability
- Affordability
- Cost-benefit analyses

components can now exist as a single component. For some applications, a smart material can be substituted for existing components, reducing overall size and complexity. Smart materials have also opened the door for the development of many novel sensors, actuators, and structural components not previously possible.

Recent progress in developing improved actuation materials, including electroactive ceramics, magnetostrictive alloys, and SMAs, is notable. Figure IV-1 summarizes some of the characteristics of various actuation materials [138]. Improvements in conventional actuator materials, discovery of new actuation materials, and their commercialization in actuator devices are described in the following sections.

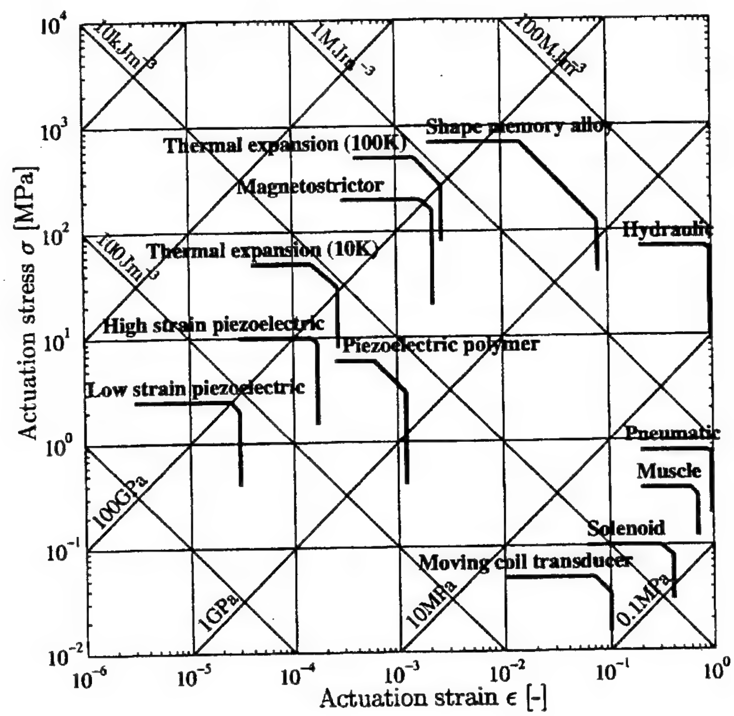

Figure IV-1. Performance Comparison of Various Actuator Materials: Actuator Stress as a Function of Actuation Strain, With Heavy Lines Bounding the Upper Limits of Performance (Courtesy of the Royal Society of London)

1. Electroactive Ceramics

Electroactive ceramics are among the most widely investigated of the "smart" materials. The powders required to form these electroactive ceramic materials into useful shapes for actuators are manufactured by several domestic companies, including APC International, Edo Corporation, Morgan Matroc, Channel Industries, and Piezo Kinetics,

Inc.[23] Other domestic companies also produce them, generally for their own internal use (e.g., TRS Ceramics). These powders are also available from foreign sources.

The best-known group of smart materials is the piezoelectric ceramics, which produce a small shape change from an applied voltage.[24] Piezoelectricity is a linear coupling between electric and mechanical variables.[25] When an external force is applied, the charge centers of the crystal structure separate, creating electric charges on the surface of the crystal and a change in polarization in the material. Electric polarization is proportional to mechanical stress in the direct piezoelectric effect. The thermodynamically related converse effect relates mechanical strain to the applied electric field. Electric charges on the crystal will cause a mechanical deformation. Piezoelectric materials can, therefore, be used for sensing and actuation. The piezoelectric ceramics have limited strain-to-failure capability but have a wide frequency response range and fast response time and a fairly large force output. Shape changes can happen very quickly, so piezoelectric components have been used in high-frequency applications, such as vibration control, audio speakers, and ultrasound generators. To date, PZT is the most widely used piezoelectric ceramic for smart structure applications. Piezoelectric polymers, such as polyvinylidene difluoride (PVDF), can also be used as actuators in some specific applications, but they are more often fabricated into ultrathin film sensors that can be bonded onto a variety of materials, including metallic or composite sheet. Other active polymers with unique properties are being developed at NASA-Langley [e.g., 139–141].

Relaxor-ferroelectrics are similar to piezoelectrics except the strain is produced by the second-order electrostrictive effect as opposed to the first-order effect.[26] Electrostriction[27] is a quadratic relationship between mechanical strain and the square of the electric polarization. It is normally a small effect, but electrostrictive strain can be surprisingly large near the Curie temperature of a relaxor-ferroelectric material. Lead magnesium niobate–lead titanate (PMN–PT), an example of such a material, can produce 0.1 percent strain at 1 kV/mm. The advantages of these materials in actuators include

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23 Other information about companies who make electroactive ceramic materials and devices can be found on the following Web site: http://eis.jpl.nasa.gov/ndeaa/nasa-nde/nde-aa-l/piezoceramics-mnfg.html.

24 Typical materials include specific compositions of PZT, PLZT, and lead magnesium niobate (PMN).

25 Only solids lacking a center of symmetry show piezoelectricity, a third-rank tensor property.

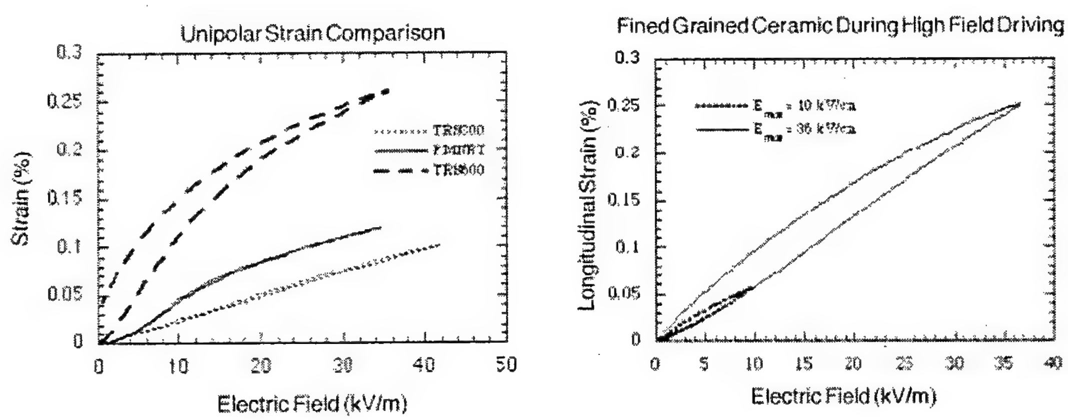
26 Typical materials include specific compositions of PMN and PLZT.

27 Electrostriction is a fourth-rank tensor property observed in all insulating solids regardless of symmetry.

improved stroke, low hysteresis, and a return to zero displacement when voltage is suddenly removed. These materials are not susceptible to stress depoling, contrary to conventional piezoelectric materials, although they are sensitive to temperature and exhibit nonlinear performance that may require application of a bias voltage.

2. Fine-Grained Ceramics

Fine-grained piezoceramics have been shown to provide improved mechanical and dielectric strength and improved machinability over conventional, coarse-grained materials. Currently, fine-grained ceramics have a 30-percent higher bending strength than conventional ceramics. This improved strength translates to higher manufacturing yields during the slicing or lapping of thin plates, important in multilayer stack actuator fabrication. The use of thinner layers in multilayer actuators, in turn, enables the use of lower driving voltages. In addition, the higher dielectric breakdown strength of fine-grained ceramics means that actuators made from them can be reliably driven to higher electric fields, a feature that results in a corresponding two- to three-fold increase in strain capability. Figures IV-2a and IV-2b illustrate achievable performance improvements in fine-grained materials [142].



(a) Comparison of Fine-Grained PZT With Conventional PZT and PMN

(b) Behavior of Fine-Grained PZT During High Field Driving

Figure IV-2. Benefits of Fine-Grained PZT Actuator Materials (Courtesy of TRS Ceramics)

3. Ferroelectric (FE)-to-Anti-Ferroelectric (AFE) Phase Switching Ceramics

FE-to-AFE switching materials undergo a phase change (with accompanying unit cell dimensional changes) upon application of an electric field. Electric field-induced AFE-to-FE phase changes are accompanied by:

- High strains arising from the AFE tetragonal to FE rhombohedral phase change
- Large hysteresis
- Shape memory effects (for some compositions).

Much of the recent work in developing AFE-to-FE phase switching ceramics has focused on the lead-lanthanate-stannate-zirconate-titanate (PLSnZT) system shown in Figure IV-3 [143]. In this system, strains of 0.5 percent can be achieved in single crystals, and strains of 0.2 percent can be achieved in polycrystalline materials. These materials can be tailored to some degree to fit specific applications.

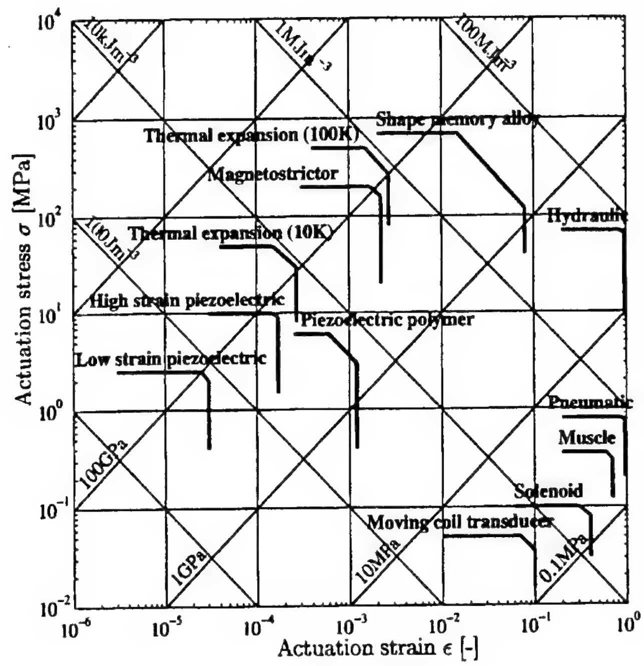


Figure IV-3. Phase Diagram of the PLSnT System Showing the Composition Region of FE-to-AFE Phase Switching Materials Under Development (Courtesy of PSU)

4. Single-Crystal Piezoelectrics

Recent breakthroughs in crystal growth methods have resulted in the development of larger FE single crystals with extremely large piezoelectric effects. Current growth methods result in large numbers of crystals approximately 1 cm^3 in size (see Figure IV-4), which are ideal for fabricating plates for high-displacement, high-force actuator stacks. The new crystals are also stronger than other piezoelectric crystals, such as quartz and lithium niobate ($LiNBO_3$). The crystals have very high electromechanical coupling factors (greater than 90 percent), making them attractive candidates for broad

bandwidth transducer applications. Field-induced strains are greater than 1 percent, which is an order of magnitude greater than the strains produced in conventional piezoceramics. These high strains result from a combination of high d_{33}'s (greater than 2,000 pC/N) and breakdown fields greater than 150 kV/cm [e.g., 142]. Although these materials exhibit many desirable properties, currently available materials are quite stress sensitive, and this behavior may limit their utility in the short term. Note that single-crystal fibers are being developed as part of a DARPA-sponsored program on single-crystal AFCs.[28] Since the materials are ceramics they are mechanically brittle and are, therefore, not directly useable under tensile loading conditions.

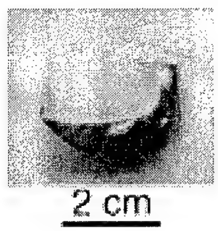


Figure IV-4. PZN–PT Single Crystal Grown by Flux Method at TRS Ceramics, Inc. (Courtesy of TRS Ceramics)

5. Shape Memory Alloys (SMAs)

SMAs make up another important group of smart materials. Several companies are capable of providing the materials. Memry Corporation, the largest of these, has international ties to other organizations and companies. Several other small companies are also capable of working with the materials to make product forms useful for devices (e.g., Specialty Metals). The term "shape memory" refers to a thermomechanical phenomenon in which a solid possesses the ability to undergo shape change at low temperature and retain this deformation until it is heated, at which point it returns to its original shape. This "memory" is reversible. In returning to its original shape, the SMA generates large forces. Large shape memory effects occur in certain intermetallic compounds with martensitic phase transformations. At least 18 known alloy systems exhibit the shape memory effect, but, at present, only three are of commercial importance: nickel-titanium alloys,[29] copper-zinc-aluminum, and copper-aluminum-nickel. Such metals are specially deformed in the low temperature martensitic state but return to their

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28 The fiber manufacturers involved in this project, led by Continuum Control Corporation, include Saphikon, Advanced Cerametrics, and CeraNova Corporation.

29 NiTiNOL, an alloy named for the laboratory at which it was developed—Nickel Titanium Naval Ordinance Laboratory—is the most commonly used SMA material.

original shape when transformed to the high temperature austenitic state. For example, a 0.01-in. diameter NiTiNOL (nickel and titanium) wire can generate 10 N of force (26,000 psi) while straining 5 percent of its original length. SMAs have been used in many temperature-sensitive applications, such as fuel control valves, surgical equipment, and aerospace equipment.[30] Significant research has been directed toward demonstrating these alloys in shape-changing structural components. These materials, in contrast to electroactive ceramics, are more ductile and, therefore, can be used in situations involving tensile and/or compressive loads. When embedded in composites, NiTiNOL wires can dampen vibrations and actively reduce stress concentrations by shifting the natural frequency of the surrounding material. Thus, NiTiNOL has potential for application in powertrain mounts and suspension bushings and in tendon devices that replicate muscle action. For dynamic applications, the cycle times are severely limited to the range of 0 to < 5 Hz because of thermal time constants.

New classes of SMAs—magneto-shape memory alloys—that can be actuated with a magnetic field are under development [e.g., 144–146]. To overcome the bandwidth limitations of conventional SMAs, nickel-manganese-gallium, iron-palladium, and iron-nickel-cobalt (titanium) alloys are some of the target compositions being examined. Typical strains on the order of 1.4 percent have been achieved, but the blocking stress is low at 8 MPa [e.g., 141]. MIT researchers have measured strains as high as 6 percent in small crystals of NiMnGa [e.g., 147].

Shape memory ceramic materials, such as lanthanum-doped PZT, are being developed [e.g., 148]; however, these materials do not exhibit strain capabilities anywhere near those of the metal alloy materials. Shape memory thermoplastics that display behavior similar to that of SMAs are also being developed [e.g., 149]. These polymer materials can exhibit relatively high strain performance, but force capabilities are lower.

6. Magnetostrictive Materials

Certain ferromagnetic materials undergo elastic strains when subjected to an external magnetic field. Induced strains and maximum stresses are on the same order of magnitude as those for piezoelectrics.

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30 There are transition temperature limits, a function of the alloy composition, that prevent the binary materials and some ternary variants from being used at very high or very low operational temperatures.

TERFENOL–D[31] is the most studied and the most used magnetostrictive actuator material. The primary domestic supplier of these materials is Etrema Products. TERFENOL–D produces a 0.2-percent strain in a 100 kA-turns/m magnetic field. Although such strains are larger than those achievable in piezoceramics, optimum performance requires that a stress be applied to the magnetostrictor before actuation. One major disadvantage of magnetostrictive actuators is the need for a magnetic field to produce actuation. This is typically accomplished using a coil wrapped around the material, which, in turn, makes the device bulky and heavy. Losses in the coils can also be high. TERFENOL materials are intermetallic alloys that are also brittle. Like the electroactive ceramics, they are used to actuate in compression.

7. Other Smart Materials

Many other types of "smart" materials exist, including electro- and magneto-rheological fluids and elastomers, which change their viscosity with application of electric or magnetic fields. Lord Corporation is one of several organizations involved in making products using these fluidic materials.

Photostrictive and chemostrictive polymer materials are also being developed. A sizable change in shape is observed in these two classes of materials when they are exposed to light or chemical environments. These effects are caused by changes in electronic structure or in chemical bonding and are usually not connected with domain-wall motion. These materials are not described here.

B. DEVICES

Performance of the individual elements in a smart structure (e.g., sensors, actuators, signal processing electronics, power conditioning and control electronics) will be critical to a completely integrated system.

1. Sensors

The most important performance parameters for fiber-optic and piezoelectric sensors include [e.g., 150, 151]:

- Reliability/durability
- Consistent, predictable response

31 TERFENOL–D is also named for the laboratory at which it was developed: TER (Terbium) FE (Iron) Naval Ordinance Laboratory.

- Low cost (important if many devices are required)
- Mechanical tolerances (device fit and finish for improved manufacturability)
- Ability to handle an acceptable range of temperatures (composite processing temperatures for embedded devices and operational temperatures)
- Aging and environmental effects (stable performance over long periods of time)
- Sensitivity (figure of merit, varies with sensor type)
- Electrical bias (for electrostrictive ceramics, complicates use).

Various types of fiber-optic sensors (e.g., extrinsic Fabry-Perot interferometers, short- and long-period Bragg grating sensors) are frequently used because of their low weight, small size, high sensitivity to strain, multiplexing capability, and lack of electromagnetic interaction (EMI) [e.g., 151]. Figure IV-5 shows schematics of several types of these sensors. While these sensors have a relatively large strain-to-failure behavior relative to other devices, they are fragile and require special handling procedures in manufacturing, particularly when they are being embedded. Fiber optics require an external power supply to generate the light source and analyze the signal. Signal interpretation is also an issue since the output is not electrical, but they have a demonstrated ability to measure strain [e.g., 151, 152] and detect vibration [e.g., 153]. The issue of separating thermal effects from strain caused by loads—a particular signal-interpretation issue—has been addressed using several approaches. A particularly promising approach is a special variation of long-period Bragg grating sensors [e.g., 151]. A significant amount of work is being done to develop fiber-optic sensors for real-time composite cure monitoring, integrity monitoring, and configuration monitoring of aerospace structures [e.g., 154]. A fiber-optic sensor capable of measuring chemical composition, strain, and temperature is currently under development. Both single and multimode optical fibers with and without Bragg gratings have been investigated. Chemical spectra of a high-performance epoxy resin were obtained using both types of fibers.

Piezoelectric ceramics and polymers are also highly sensitive to strain, have easily measured electrical outputs, and have the added advantage of no requirement for an external power source. However, they suffer from EMI constraints. If embedded in composites, electrical shielding is necessary. There are also temperature limitations, and ceramics are limited by a relatively low strain-to-failure behavior.

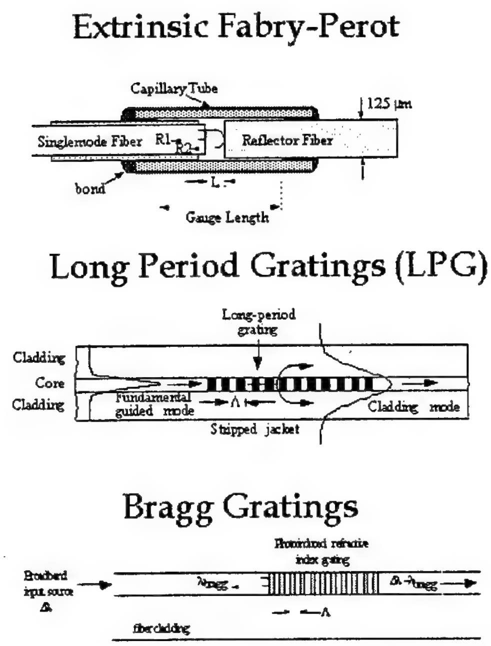

Figure IV-5. Schematic Diagram Illustrating Various Fiber-Optic Sensors (Courtesy of Luna Innovations)

Some manufacturing techniques for embedding sensor packages with minimal disturbance to the structure have also been developed. Figure IV-6 shows a strain gage rosette designed to be embedded 0.25 in. below the surface of a graphite-fiber-reinforced epoxy composite. The strain rosette is remotely powered and interrogated using an RF link that powers the device and reads the strain results.

2. Actuators

Desirable features for actuators include [e.g., 7, 8, 9, 87, 88, 138, 150]:

- Consistent and predictable device-to-device and cycle-to-cycle response
- Extreme mechanical tolerances (especially surface parallelness and flatness in electroactive ceramics)
- Low (or at least predictable) hysteresis
- Low creep (important when actuators must hold a position for a "long" time)
- Large force/load-carrying capability (generally a tradeoff with displacement capability) and large dynamic range
- High frequency response (application-dependent need)
- Linearity (displacement with respect to applied field)
- Capacitance (for electroactive ceramics, important in high-frequency applications for which drive current is a concern)

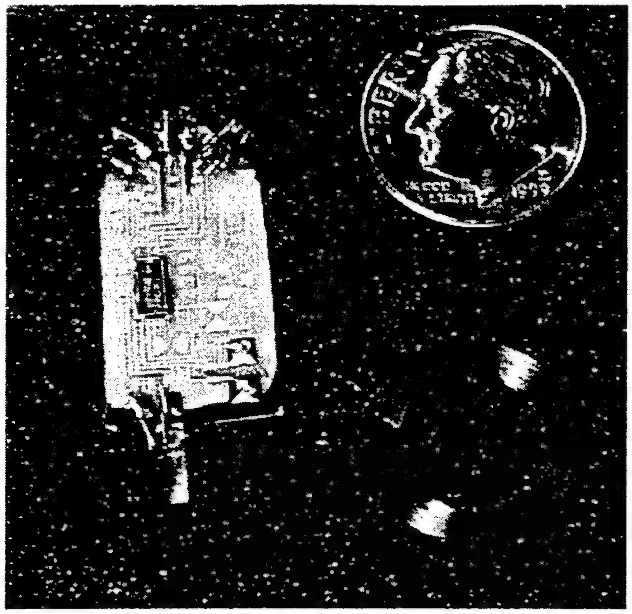

Figure IV-6. Remotely Queried Strain Gage Rosette Designed To Be Embedded in Graphite-Reinforced Polymer Matrix Composites (Courtesy of NRL and MTS Corporation)

- Durability and reliability over time, including aging and environmental effects.

Smart-material-based actuators exhibit some, but not all, of these characteristics. While significant emphasis has been placed on developing the smart materials, much less effort, in general, has been focused on developing devices that take full advantage of their unique properties.[32] Several studies to investigate relevant properties—primarily electrical and mechanical fatigue characteristics [e.g., 87, 88] and power and energy characteristics [e.g., 155, 156]—of available actuator devices to determine their suitability for particular applications are in process or have been completed, but much more work remains to be done. The following sections describe actuator devices—some standard products available in large quantities and some developmental products available in small batches or single units—made using electroactive ceramics, SMAs, and magnetostrictive alloys.

a. Piezoelectric Ceramic Actuators

Ceramic actuators are found in a variety of forms: thin plates [e.g., 157], multilayer stacks [e.g., 158], injection-molded shapes [e.g., 159], and fibers [e.g., 160].

32 At least until recently, DARPA has just initiated a new Compact Hybrid Actuator Program to address this very issue.

Thin-plate-type actuators are more or less a standard product and have been used in many vibration-suppression applications [e.g., 9, 71, 106]. Fibers are a developmental product at present.

Some of the several domestic "manufacturers" of piezoelectric disks, plates, and tubes include APC International, AVX,[33] Channel Products, Keramos, Materials Systems, Inc., Motorola, Rockwell, Xinetics, Aura Ceramics, Channel Industries, Edo Corporation, Lockheed Martin (Palo Alto), Moran Matroc, Piezo Kinetics, Inc., and TRS Ceramics. Generally, companies that can make disks or plates can, on principle, also produce conventional glued stacks (e.g., Materials Systems, Inc., TRS Ceramics). Any company that processes co-fired multilayer ceramic capacitors or substrates (e.g., AVX, Xinetics) can, on principle, produce co-fired stacks. Developmental quantities of piezoelectric fibers are available domestically through CeraNova Corporation and Advanced Cerametrics. Several domestic companies also produce transducer and actuator devices, including those companies identified above and ACX, Burleigh Instruments, and PCB Piezotronics, among others. Continuum Control Corporation is using the piezoelectric fibers to manufacture AFC patch actuators. Japanese device manufacturers[34] include Tokin Corporation, NEC, Hitachi Metal, Mitsui-Sekka, Canon, and Seiko Instruments. European actuator manufacturers[35] include Philips (The Netherlands), Siemens (Germany), Hoechst CeramTec (Germany), Ferroperm (United Kingdom), and Physik Instrumente (Germany). Since all available actuators can not be described here, only a few significant and/or innovative examples are cited.

The ACX QuickPack® actuator, used in several of the major demonstration projects described previously, is a thin, flat piezoceramic device that creates linear motion (see Figure IV-7a). Used as a strain actuator, it extends with applied voltage while bonded to the surface of a structure. Used as a bimorph actuator, it bends with applied voltage while clamped firmly at one end. ACX has developed an adaptive SmartPack™ combining sensors, actuators, and power and control circuits in an integrated package that

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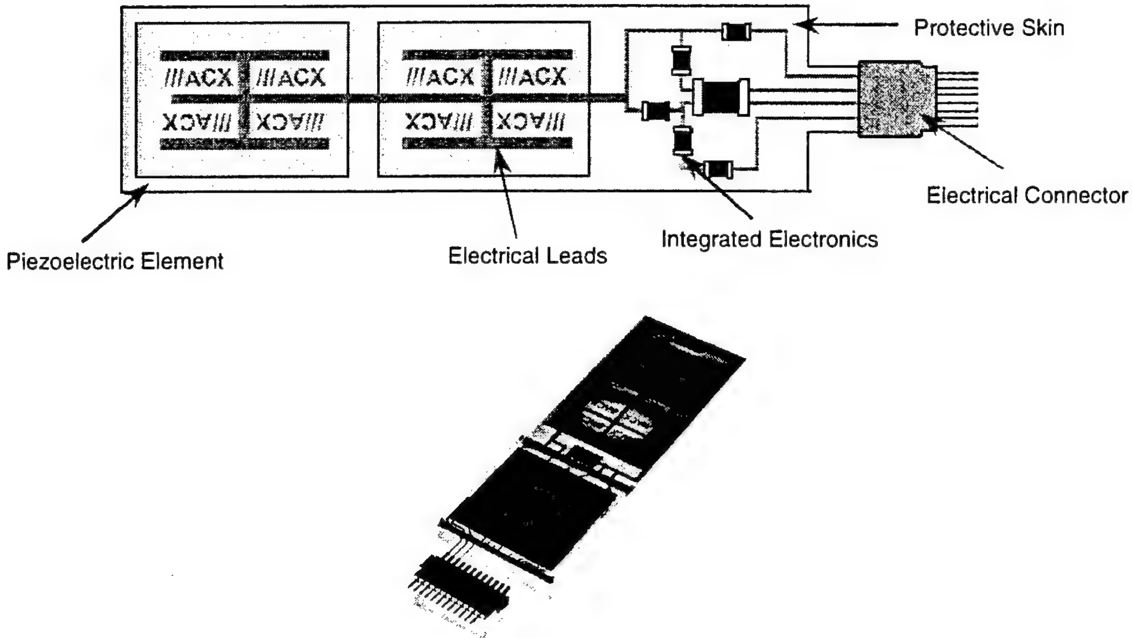
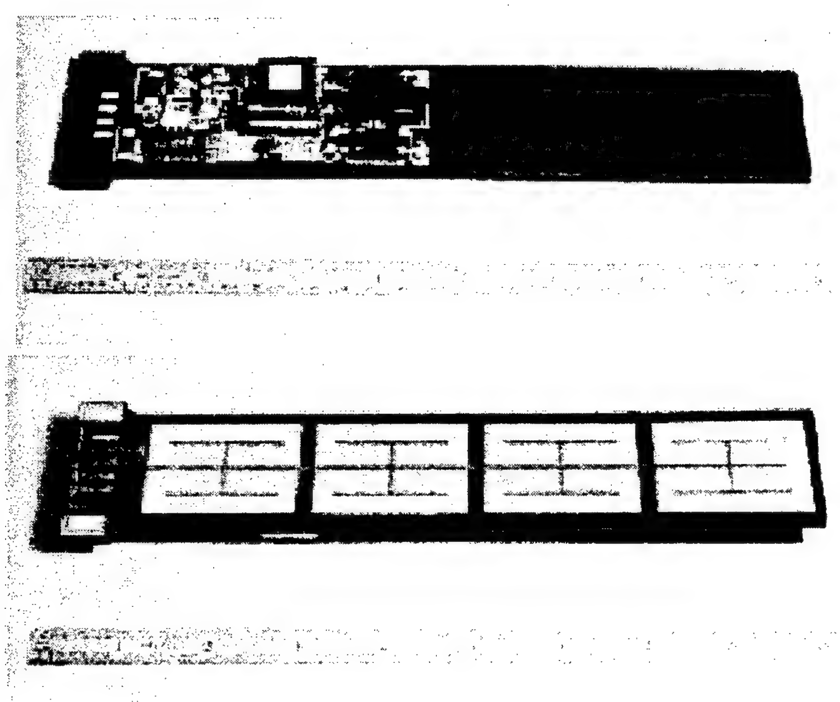
33 AVX is a commercial supplier of capacitors. They have adapted their production process to make tiny chiplet stacked actuators but will only sell large orders.

34 Applications are targeted toward miniature motors and positioners for mass consumer products and include office equipment, cameras, precision machines, and automobiles.

35 Applications are targeted toward miniature motors and positioners for lab equipment and vibration suppression and include lab stage/steppers, airplanes and helicopters, automobiles, and hydraulic systems.



(a) The QuickPack™ Actuator



(b) The SmartPack™ Actuator Containing Integrated Electronics

Figure IV-7. ACX™ Actuators (Courtesy of ACX)

automatically detects and adapts to uncertain structural mode frequencies (see Figure IV-7b).

NASA-Langley has also sponsored and developed two unique configurations of piezoelectric actuators: Reduced And INternally Biased Oxide Wafers (RAINBOW) [e.g., 161–164] and THin layer UNimorph DrivER (THUNDER) [e.g., 165, 166]. In contrast to the piezoelectric patch actuators, which are flat and actuate primarily in-plane, these actuators are dome shaped and actuate out-of-plane. Both devices exhibit displacements several orders of magnitude greater than conventional piezoceramic actuators but at the expense of actuator authority.

RAINBOW actuators are produced by reducing one side of a piezoelectric wafer during firing by using an additional heat treatment step. In the RAINBOW process, developed at Clemson University [161], typical PZT wafers are lapped, placed on a graphite block, and heated in a furnace at 975 °C for 1 hour. The heating process causes one side of the wafer to become chemically reduced. This reduced layer, approximately one-third of the wafer thickness, develops internal strains in the wafer that shape it into a dome. These internal strains cause the material to have higher displacements and higher mechanical strength than a typical PZT wafer [167]. RAINBOWs with displacements of 3 mm and point loads of 10 kg have been reported [162]. Since many applications will require continuous, long-term operation of high-displacement piezoelectric actuators, fatigue characteristics of these materials and devices have also been measured [e.g., 168].

THUNDER [e.g., 165, 166] is a fairly new actuator that was developed at NASA-Langley. These devices are unimorph-type actuators that consist of a piezoelectric ceramic layer bonded to one or more nonpiezoelectric secondary layers. THUNDER actually refers to the process for packaging the ceramics. A metal sheet is laminated to the ceramic under heat and pressure to place the ceramic in a pre-stressed state, giving it a domed shape as shown in Figure IV-8.[36] Such packaging offers increased environmental resistance and improved durability while maintaining the basic electrical properties of the piezoceramic. The THUNDER actuators operate from the direct current (DC) into the megahertz region and have displacement-to-weight ratios that are orders of magnitude greater than those of other actuators in the market today. Currently, the processing and characterization of THUNDER high-displacement actuators are under investigation. One recent characterization effort [169] studied the effects of electric field, load, and frequency on the displacement properties of rectangular THUNDER devices.

36 The major features that determine the operating parameters of a THUNDER actuator are the type and thickness of piezoceramic, the curvature, number of layers, thickness and placement of the foil stressing member, and the thickness of the adhesive.

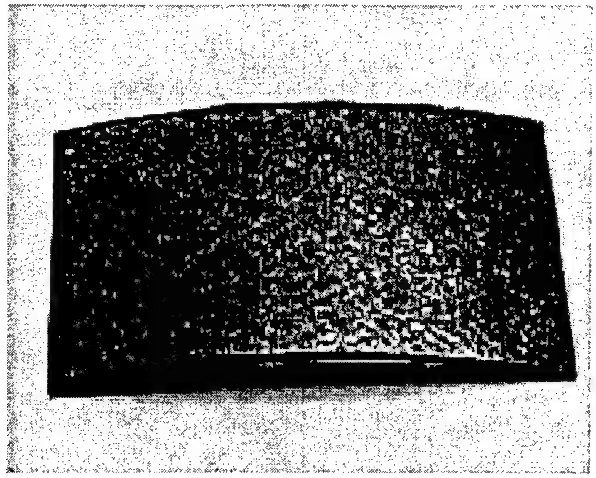


Figure IV-8. The THUNDER Actuator Showing Its Domed Shape (Courtesy of NASA-Langley)

A related study [170] focused on identifying the material characteristics (e.g., creep, hysteresis, and fatigue) and the airfoil shaping effectiveness of the THUNDER piezoelectric technology under aerodynamic loading. Results indicate that these new actuators are promising candidates for future airfoil shaping investigations.

The NRL is developing a piezoelectric torsional actuator [171]. This device uses segmented piezoelectric materials assembled to form a cylinder. Application of an electric field causes the cylinder to twist in torsion. The device is being configured to operate as a solid-state motor so that large rotation angles can be achieved.

Continuum Control Corporation has developed a manufacturing process to make AFC patches. The piezoelectric fibers (see Figure IV-9a), which provide the stiffness and actuation authority, have a diameter of 137 μm. The interdigital electrodes—with a kapton electrode substrate and a silver electrode—are 25.4 μm thick. Total pack thickness is on the order of 215 μm. Figure IV-9b shows several of their standard AFC packs. The standard pack used in the rotor blade twist application—fibers are oriented at 45 deg—exhibits an average actuation strain of 1,200 μstrain. Operational voltage limits are –1,500 to +2,800 V.[37]

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[37] Efforts are underway to reduce the voltage requirements for these packs. The high-voltage requirement limits their use at present.

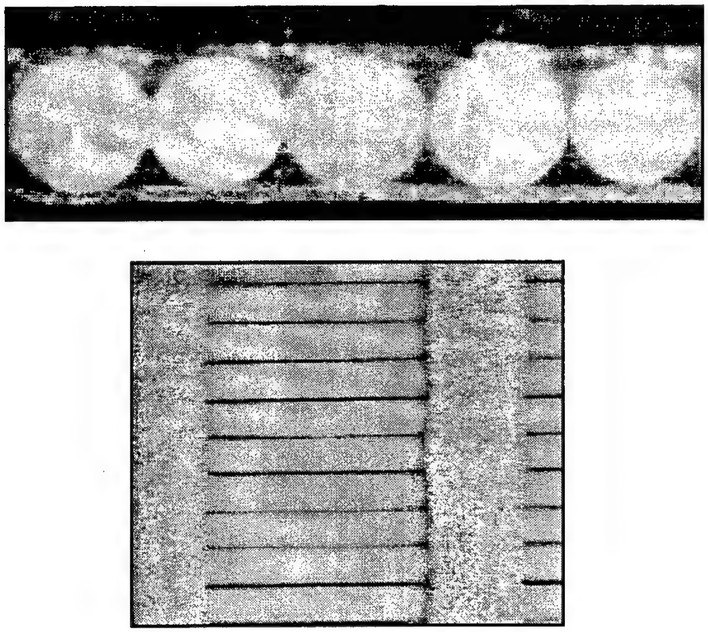

Figure IV-9 (a). PZT-5A Piezoelectric Fibers Used To Make AFC Packs (Courtesy of Continuum Control Corporation)

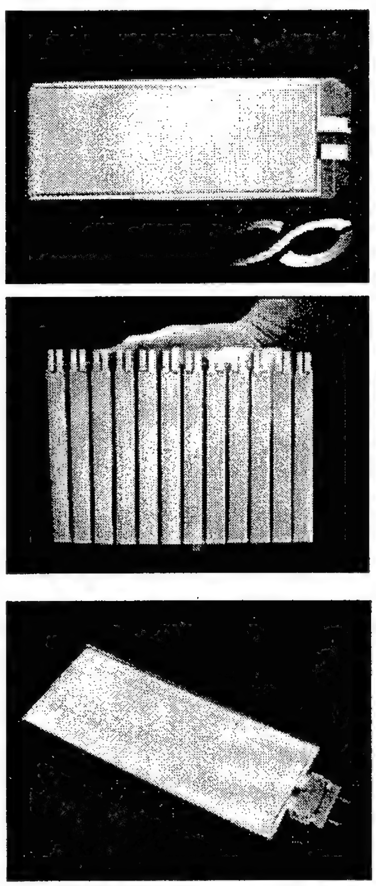

Figure IV-9 (b). Several Sizes of AFC Packs (Courtesy of Continuum Control Corporation)

b. SMA Actuators

SMA actuators, which work via a temperature-induced microstructural phase change in the material, exhibit relatively large actuation forces (recovery forces), high strain (recovery strain) output, and good damping capabilities, but these actuators may also exhibit large hysteresis. The temperature at which the phase transition occurs and the amount of observed hysteresis can be adjusted by changing the material composition [e.g., 172]. Typical forms include wires, rolled foils or sheets, and torque tubes.[38] Some researchers are examining sputtering techniques to deposit thin films for micro-scale devices [e.g., 173]. The actuation mechanisms and control approaches can be fairly simple in design, an advantage over other types of actuators. However, because of their slow response time (attributed partly to the slow cooling capacity of the material), they are best suited for low-frequency applications, on the order of a few hertz or less. Operational parameters, such as temperature, time at temperature, stress levels, required transformation strains, and number of transformation cycles, will affect the long-term durability of these devices. The SMAs are quite suitable for slow motion of control surfaces, such as flaps in helicopters [e.g., 86] or trailing edges in aircraft [e.g., 114].

Both Boeing and Northrop Grumman have evaluated nickel-titanium-copper SMA torque tubes for application in helicopter and tilt-rotor blade twist and for shape adaptive wings. Smaller torque tubes sized for 100 in.-lb and operating at ~ 0.2 Hz have been fabricated for use in helicopter blades. More robust SMA torque tubes have been developed for use in the Smart Wing programs. For example, the Smart Wing Phase I program actuator (see Figure IV-10) has a blocking torque of 3,500 in.-lbs and operates at ~ 0.03 Hz. This work has established design guidelines for sizing SMA torque tubes [86, 117, 173].

Other SMA devices include shockless release mechanisms [41] for spacecraft application (see Figure IV-11). These devices provide considerable improvement over pyrotechnic release devices. Shock separation reductions of 10X or more are achievable

[38] These standard product forms are available from a number of sources such as Memry Corporation and Specialty Metals, among others; custom shapes can be fabricated on demand. The primary applications for devices assembled with these standard product forms are medical and industrial products (e.g., NiTi Alloys Technologies, LTD, Raychem Automotive, Shape Memory Applications, Inc., and Intrinsic Devices, Inc.). SMA devices for air and space applications are not true commercial products: made a few at a time, they are designed specifically for an application and are usually designed, fabricated from custom shapes, and assembled by one of a few companies (e.g., Lockheed Martin-Denver, and ITN).

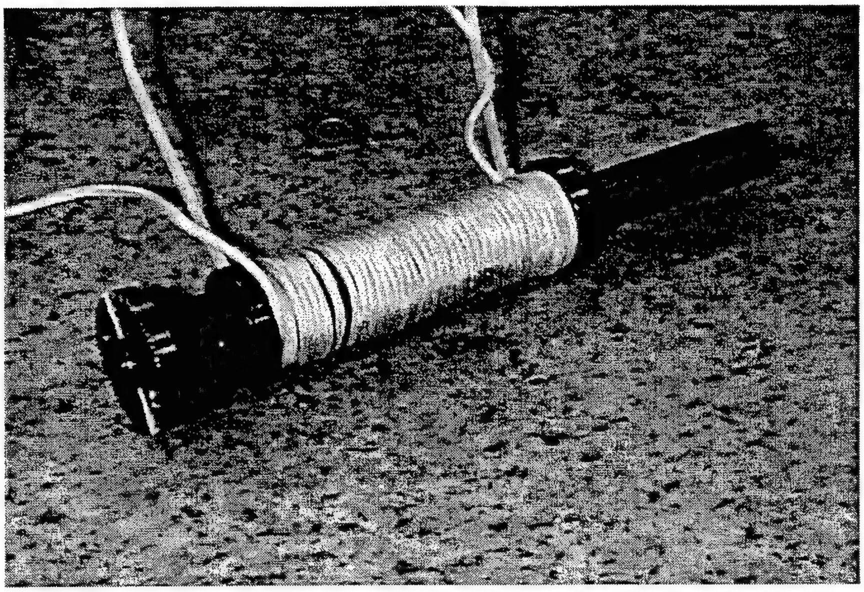

Figure IV-10. The Smart Wing Phase I (Wind-Tunnel Entry 2) SMA Torque Tube (Courtesy of Northrop Grumman)

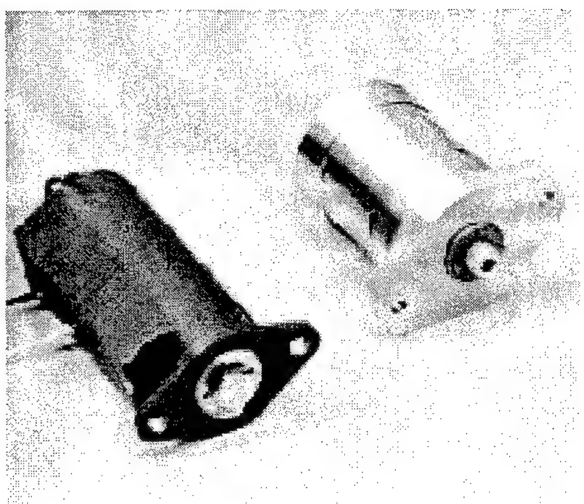

Figure IV-11. SMA Shockless Release Devices (Courtesy of Lockheed Martin Astronautics)

using these SMA devices. These devices have been flight-tested in the SMARD MightySat-1 experiment described earlier. SMA rings for turbine engine blade tip clearance control [174] are also being examined.

c. Magnetostrictive Actuators

The rare-earth magnetostrictive alloys have high force and strain capabilities but are extremely heavy, and magnetic field shielding is an issue. These actuators are often found as rods or multisegmented stacks [e.g., 175]. A group at Northrop Grumman and

Etrema Products, Inc.,[39] examined use of a magnetostrictive linear motor for controlling air foil shape of transport aircraft to optimize performance (e.g., improved lift/reduced drag, increased range, reduced fuel consumption) over a range of flight conditions [120]. The motor achieved 20.1 lbf with a stroke of 0.75 in. [176]. As mentioned previously, the performance benefits were not sufficient to pursue this concept without significant reduction in the actuator mass. AFRL is funding a Small Business Innovative Research (SBIR) project at Etrema to develop a self-contained, hybrid magnetostrictive pump in support of the All-Electric Aircraft program.

NASA-Goddard is supporting efforts at Etrema Products, Inc., to develop a magnetostrictive actuator that operates at cryogenic temperatures for use on the Next-Generation Space Telescope and on other cryogenic devices, such as switches and valves. These devices use modified TERFENOL alloy chemistry to adjust the magnetostrictive properties for low-temperature use [177].

3. Other Concepts and Issues

Because the performance capabilities of currently "available" actuators are still orders of magnitude inadequate to address many application needs for large structures (e.g., aircraft wings), some researchers are investigating hybrid devices combining hydraulics and electroactive ceramics or magnetostrictives [e.g., 178]. Others are investigating the use of small-scale devices—MEMS—to alter airflow over a surface. For example, the location of local flow separation over a wing could be changed by the placement of microactuators at the leading edge [e.g., 179]. One problem with this concept is that MEMS devices are fragile, which may preclude their use in many situations. As another example, aerodynamic shapes could be modified or the turbulence, pressure gradients, and flow noise could be controlled by placing synthetic jets or "puffers" across the skin of the wing or in an engine air inlet [e.g., 180].

To help meet the expected future requirements for environmentally robust, durable, low-power, high-authority, high-strain, fast-response actuators, DARPA initiated several new programs to develop higher authority actuator materials, including, among others, SMAs, single-crystal electroactive ceramics, piezoelectric fibers, and injection-molded piezoelectric ceramics. A new DARPA program will focus on compact hybrid actuation schemes that address integrated electronics and power issues.

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[39] Etrema Products, Inc., is the primary supplier of these devices.

Considering issues not only associated with the materials and devices themselves but also how they will be used in real applications is important.[40] As an example, one research issue identified in the PARTI program concerned piezoelectric power consumption during active control. One of the techniques being investigated in the Aircraft Morphing program for control of larger, realistic structures is passive or active damping augmentation using shunted piezoelectric actuators. This method, which uses a parallel inductor and resistor to shunt the piezoelectric actuator electrically, may provide an alternative to active control using conventional (unshunted) piezoelectric actuators. Two key benefits of using shunted piezoelectric actuators for damping augmentation are the very low power required for operation of the circuit and the simplicity of mechanical operation when the shunted actuators are used passively for control.[41] A recent NASA study [181] realized up to 70-percent reduction in aeroelastic plunging response via shunted piezoelectrics. The study also showed that the effectiveness of the shunted piezoelectrics was a strong function of the inherent structural and aerodynamic damping. While this method may not be as effective for highly damped structures (some applications may require active control to achieve the desired system performance), shunted piezoelectrics can provide a simple, low-power, fail-safe vibration-suppression method for lightly damped structures. Future research activities include conducting open- and closed-loop experimental ground tests on large-scale structures to assess tradeoffs in piezoelectric control effectiveness. Power consumption and optimal control strategies using active and passive control techniques with shunted and conventional, unshunted piezoelectric actuators will also be investigated. The shunted piezoelectric actuator studies will be accomplished in collaboration with Boeing (Huntington Beach) [e.g., 182]. During ground tests, comparisons and tradeoffs between control effectiveness and power consumption of the active control vs. active/passive damping control will be performed.

C. HARDWARE INTEGRATION

The use of actuators, sensors, and controllers to alter the performance of structures is becoming a viable option for designers. While much progress has been made in controlled structures technology over the past decade and many new types of

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40 This subject is addressed in more detail in the System Integration section (see p. IV-35).

41 This is in contrast to several issues arising when piezoelectric actuators are used for active vibration control: the potentially high amount of power needed and the corresponding weight and volume of the actuators, power supplies, and amplifiers required.

devices—sensors and actuators—have been developed, there are still issues associated with integration of all these features into a real system. Integration can be approached from two perspectives: the first is focused on practical manufacturing issues associated with actual/physical integration of smart materials into real components and is addressed here; the second, a "big picture" perspective, is focused on larger system considerations and is addressed later.

1. Practical Manufacturing Issues

Practical problems associated with building smart structures and implementing them in real systems represent a significant barrier. To date, most examples of controlled structures involve surface mounting or bonding the sensors and actuators. This approach often carries the least risk since the passive structural load paths are unaltered and failed components can be readily identified and repaired or replaced. Surface mounting is appropriate for some types of actuators, such as inertial proof-mass actuators and displacement/force actuators connecting the controlled structure to ground. However strain actuators, which create a relative displacement within the structure, are usually most effective when they are embedded into the structural elements [e.g., 183]. Except for simple structural geometries, such as beams and plates, surface mounting of strain actuators leads to less control authority than when they are embedded and their impedance is matched to the host structure. Structural integration of the actuators, sensors, power and data electrical buses, and, perhaps, the controller electronics should also lead to more robust, durable, controlled structural systems. Numerous challenges arise when embedding smart materials into composite structures, including, among others [e.g., 183]:

- Electrical circuit failures caused by dielectric breakdown and arcing
- Breaking of ceramic wafers and electrical leads (particularly in curved surfaces)
- Low performance caused by impedance mismatch or temperature changes
- Compromised structural integrity caused by microcracking and macrocracking in the host composite material.

These complications have been encountered in low-to-moderate strain-level applications but are even more problematic when high-stress, high-strain designs—typical of some aerospace applications—are pursued.

Selection of the host material/structure strongly influences the type of manufacturing and fabrication processes actually used to create the smart structure. If the devices are to be attached to a metal structure, typically achieved via adhesive bonding,

the choice is relatively easy. When devices are to be embedded in the structure, which implies a polymer composite host material, selection of the process can be more difficult. Early efforts to embed piezoelectric sensors and actuators, fiber-optics sensors, and SMA actuator wires required hand lay-up and other special handling procedures [7, 8, 184], a time-consuming and expensive process. Many current research programs are still using hand lay-up processes [e.g., 185]. Thus, user interest in developing cost-effective, automated methods to fabricate these structures has been and continues to be considerable.

2. The Synthesis and Processing of Intelligent, Cost-Effective Structures (SPICES) Program

One of the primary objectives of the joint DARPA/Industry SPICES program was the development and demonstration of cost-effective methods for fabrication of smart structures [157, 186]. This consortium evaluated two potentially low-cost techniques for embedding ACX Quickpack™ piezoelectric plate actuators, frame-type piezoelectric stack actuators, fiber optics, and SMA wires: (1) RTM for a flat plate component and (2) advanced fiber placement for a trapezoidal rail component. Concerns about device compatibility with the host material, interfaces and interconnects between the devices and the structure, methods to fix devices in place during processing, and edge egress of wires/cables from the structure were addressed. For example, to prevent shorting out of the SMA in the rail component, an SMA tow-preg consisting of SMA wires embedded in a thermoplastic sheath was developed. Special shielding methods were developed to protect the piezoelectric actuators from the laser during fiber placement. For the RTM plate, a rigid substrate consisting of SMA wires embedded in a thin, E-glass fiber-reinforced substrate was developed. In this way the fibers could easily be pre-strained. For the RTM component, registration holes were required to hold the Quickpack™ actuators in place. A unique method—a clean-trim utility conduit— eliminated the edge egress problem so no wires were hanging from the part. Lessons learned from this program are being applied in follow-on efforts.

3. Other Issues

While the SPICES program was successful in identifying and solving problems unique to their selected processes, some other issues have not been addressed to any significant degree. Some of the modeling and design issues for materials have already been identified. Other concerns include a lack of methods to calibrate embedded sensors and actuators, few reliable approaches to evaluate the manufacturability and cost of smart

structures, and a limited understanding of the environmental and operational durability of structures with embedded devices.

D. ANALYTICAL METHODS

Much progress in the area of smart structures has developed from interest in specific applications and devices, with generally limited analyses. Engineering design, calculation, and simulation methods are sorely lacking in many nontraditional disciplines, and the situation is particularly inadequate with regard to smart materials and structures. Integrating electrical, mechanical, and controls models—required for proper analysis and design of smart material devices and applications—is not possible without considerable specialization of the modeling tool set. Most existing modeling tools are not validated for the cross-coupling physics inherent in nonlinear materials/structure systems where smart materials are applied. Analysis tools, which must be well integrated into accepted tools, such as NASTRAN, ABAQUS, and MATLAB, and which are validated, are not available. Almost all smart materials applications developed to date have been designed using custom-built MATLAB or finite element code equivalent simulation models. These models are difficult to construct, modify, and extend. Furthermore, the occurrence and degree of model-simplifying assumptions are often obscured, and their aggregate effects on the bounds of validity for any given model cannot reliably be determined. As a result, relatively expensive experimental work is absolutely required, not only to verify operation and performance, but to understand the operation and its implications on system performance.

Models and analytical techniques that can reliably simulate and predict system responses are necessary to achieve effective and useful designs. One would like to begin with constitutive laws describing the active material/device behavior in terms of its inherent material properties. For example, Hom and Shankar [187] developed a constitutive model to describe electrostrictive ceramics. This fully coupled, 3-D model relates key variables (e.g., stress, strain, electric field, polarization, and temperature) based on particular material constants. As an additional example, several constitutive models (e.g., ferroelectric, internal variable, plasticity, hysteresis, and nonisothermal) have been developed to describe SMA behavior [e.g., 188, 189]. These nonlinear models rely on different characteristics and properties of the SMAs to describe stress-strain relationships, the superelastic effect and its attendant energy dissipation, one-way and two-way shape memory effects, and so forth.

Ideally, material constitutive models, such as those identified previously, would be combined with models of the active devices, structural response models of the host structure, and field equations to describe the system. The models must include all cross-coupling phenomena. Such an approach would allow for a detailed understanding of the system. At present, such complete system models do not exist, although researchers are working on individual pieces of the puzzle.

To use active devices in these systems, understanding the behavior of the actuator is critical. For example, to use THUNDER actuators in engineering applications, modeling and characterization are essential. No simple analytical models have been available to understand static and dynamic behavior of THUNDER actuators. A NASTRAN nonlinear finite element model has been developed for predicting the dome heights of THUNDER piezoelectric actuators. A simple approach is used whereby temperature-induced expansion is used to simulate voltage actuation as described by Babuska and Freed [190]. To validate the finite element model analytically, a comparison was made with the nonlinear plate solution using Von Karman's approximation. The NASTRAN finite element model was also compared with experimental results [191].

Finite element modeling and validation for patch piezoelectric actuators has been examined by several groups. For example, during the PARTI program, a finite element model of the PARTI wind-tunnel model was created, and the natural frequency and mode shape results were validated with ground vibration tests. Although global structural dynamic data—mode shape and natural frequency data—could generally be modeled with sufficient accuracy, local deformation and force data were difficult to model accurately with reasonable computational efficiency. Considerably smaller finite element mesh sizes and a judicious use of finite elements were needed to capture the abruptly changing strain field in the area immediately next to the piezoelectric actuators.

Numerous researchers have developed analytical and numerical models to analyze piezoelectrically controlled structures [e.g., 192–197]. These research efforts and others clearly show that the key considerations for modeling in-plane piezoelectric actuation are:

- More refined mesh sizing (that may be accomplished through superelement modeling) and/or higher order structural analysis theory to capture the widely varying strain field around the piezoelectric actuator
- Prudent modeling of damping to capture the dynamic piezoelectric effect more accurately

- Improved finite element modeling techniques to model larger, more complex structures with piezoelectric actuators.

As an example, Seeley's work [193] showed that the strain field in the host structure in the vicinity of the piezoelectric actuator is nonlinear. Most analyses used to model piezoelectric actuation, including the one used during the PARTI program, assume that the strain field through the thickness of the host structure is linear. Seeley [193] used higher order laminate theory, implemented via a finite element method, to model the piezoelectric actuation of composite plates. Strain measurements (via traditional gages) taken around a piezoelectric actuator may give unexpected results since most researchers assume stress and strain fields are essentially linear.

Although the previously mentioned analytical techniques can give very good theoretical results, they can also be complicated and difficult to implement, even for simple structures. Researchers at NASA-Langley are investigating and validating simple and accurate techniques for modeling structures containing piezoelectric actuators using MSC/NASTRAN[42] [198]. Finite element models of structures of increasing complexity are being developed and validated (e.g., analytical models of a simple aluminum beam and a composite box beam with surface-bonded actuators have been validated with experimental results). The analytical technique [197] involves using a finite element approach to model the structure with actuators and a thermally induced strain to model the straining of the actuators with an applied voltage field.

During the PARTI program, Pototzky [199] used a finely meshed finite element model of a cantilevered beam to develop a method for modeling the aeroservoelastic response of a structure controlled with piezoelectric actuators. His method relied on a thermal mechanical analogy to create a static deflection shape of the beam actuated by the piezoelectric actuators. This shape was then appended to the free vibration mode shapes, and the new augmented modal matrix was applied to an aeroservoelastic analysis using the Interaction of Structures, Aerodynamics, and Controls Code (ISAC) [200]. Including this deflection shape as a mode in the aeroelastic analysis may allow for computation of the aerodynamic influence of piezoelectric actuation. A very finely meshed finite element grid was used to ensure the accuracy of strain information—something that for larger, more complex models may be computationally difficult.

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42 MSC/NASTRAN was selected because it is a commonly used structural analysis code.

As in the area of finite element modeling, many researchers have developed methods to incorporate piezoelectric actuation in aeroservoelastic models [e.g., 201, 202]. Much of this work uses simplified structural models. Researchers in the NASA-Langley Aircraft Morphing program are using doublet lattice aerodynamics and the ISAC code to perform the aeroservoelastic analyses. Existing data from the PARTI and ACROBAT programs will be used to assist in verifying these analysis methods. Verification of the analysis techniques will first be conducted at zero airspeed and then expanded to correspond to wind-on data. Data from ground modal tests conducted in the Aircraft Morphing program will be used to verify zero-airspeed characteristics further. Additional simplified models may be constructed and tested to provide more experimental data to compare with the aeroservoelastic modeling development.

To be ultimately usable by a design engineer, however, faster, more efficient computational methods that retain important features of the detailed physical models are necessary. The SPICES consortium, for example, addressed this efficiency issue via the use of superelements to describe piezoelectric device behavior within the context of a large ABAQUS finite element model [157]. Results showed good agreement between experimental and predicted broadband and modal responses for simple structures. Techniques to improve this finite element modeling capability have been identified for more complex structures. As another example involving complex constitutive behavior, Regelbrugge [203] modified Hom and Shankar's electrostrictor model to evaluate the performance of a vibration cancellation device more easily. He obtained excellent agreement between test data and the model for strain polarization as a function of induced strain and of electric field.

The Air Force has supported work at CSA Engineering to develop finite-element modeling techniques for smart structures, mostly considering vibration-suppression applications, such as buffet load alleviation, flutter suppression, and component isolation. Presumably, having such models available will allow designers to characterize the collective system behavior and to evaluate system performance enhancements, such as increased lift, decreased fuel consumption, and so forth, more easily.

System models are also being developed to describe improvements in helicopter performance. For example, to investigate the potential of AFC rotors, two active twist rotor mathematical modeling methods have been developed at NASA-Langley. The first of these is a simple, mathematical aeroelasticity model for composite helicopter rotor blades incorporating anisotropic, embedded piezoceramic actuators. The computer implementation of this model, the PiezoElectric Twist Rotor Analysis (PETRA), has been

created for use with the MATLAB numerical analysis program [204] and is ideally suited for conceptual active twist rotor design and optimization studies [93, 94, 96]. A procedure for using a commercially available comprehensive rotorcraft computer code (CAMRAD II) [205] for active twist rotor studies has also been developed. This allows active twist rotor numerical studies to be performed using a detailed state-of-the-art rotorcraft aerodynamics and structural dynamics model. Figure IV-12 compares the two codes in terms of relative twist as a function of frequency for a full-scale active twist rotor blade in hover. The twist amplitude and bandwidth behavior shown here would be sufficient for many IBC applications and, for vertical hub shear vibration reduction, in particular. Agreement between the two analytical methods is also extremely good and shows that the fundamental active twist rotor dynamics are being modeled consistently.

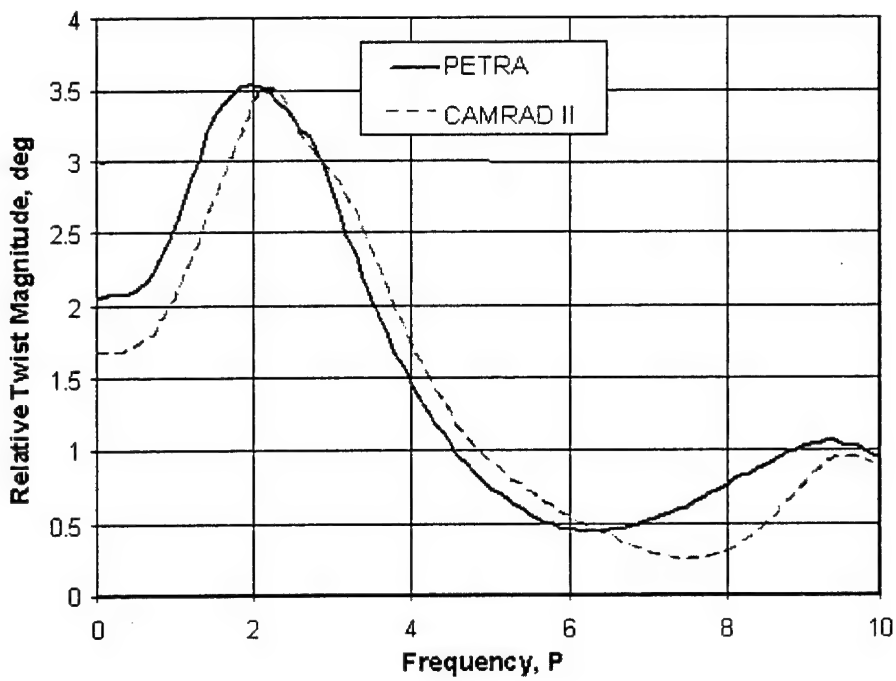

Figure IV-12. Calculated Hovering Flight Twist Actuation Frequency Response for a Full-Scale Active Twist Rotor Blade Concept (Courtesy of NASA-Langley)

Figure IV-13 shows an example of the predicted capability of AFC rotor blades to alleviate stall on helicopter rotors [96]. Rapid buildup of torsional vibratory loads caused by stall severely restricts the maximum lift and forward flight speed capabilities of conventional helicopters. Vibration trends with increasing flight speed are shown for a conceptual full-scale active twist rotor blade with and without twist actuation control. Trends for a conventional, passive-structure blade are also shown as a reference. The

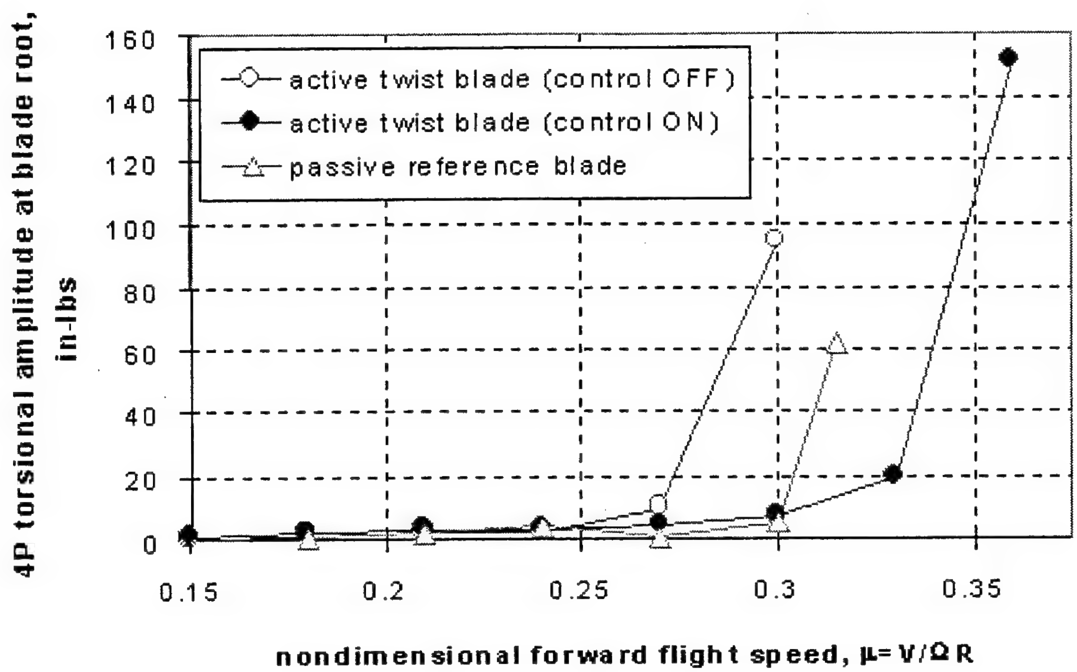

Figure IV-13. Calculated Suppression of Dynamic Stall-Induced Torsional Vibrations Through Active Twist Control (Courtesy of NASA-Langley)

rapid rise in dynamic stall-induced torsional vibratory loads for the active twist rotor blade using twist control has been effectively delayed by approximately 10 percent in nondimensional flight speed for the baseline blade and by as much as 22 percent for the AFC blade with no twist control.

Effective use of optimization models and schemes to determine the number and location of sensors and actuators needed to perform the desired task are being developed. For example, wind-tunnel results from the PARTI program showed that at a given tunnel condition, one control law using all 15 actuators reduced gust loads by 75 percent while another control law using only 6 actuators reduced gust loads by 72 percent. For many cases, such a minor loss of control effectiveness (3 percent) is inconsequential compared with the 60-percent reduction in the number of actuators required, which significantly reduces weight and complexity [83]. Two studies [206, 207] investigated choosing optimal actuators from a set already in place on the PARTI model as opposed to choosing the optimal placement of actuators. Lin's study [207] focused on the selection of set of effective actuators for improving the performance of active control at a single design point, namely, the onset of flutter. Simulation results using two control law designs showed that the optimal actuator set gave improved closed-loop performance, independent of the control law design selected.

Along with the general design approach and models noted above come a range of more specific concerns. These include:

- An inability to predict the life of the device in a free or integrated condition, especially its durability and reliability in terms of fatigue, fracture, and other mechanical performance criteria
- A lack of understanding of cross-coupling (electrical, magnetic, thermal, mechanical, fluidic, and so forth) among the various devices, the structure, and the operational environment
- No fast, reliable method for determining the correct number and placement of individual sensors and actuators within or on the structure.

Efforts to address life prediction, in particular, may require further development of nonlinear mechanics models. Such efforts will also require extensive experimental tests to simulate the end-use operational conditions and to verify models.

E. CONTROL APPROACHES AND ALGORITHMS

Control is still a challenging aspect in the smart materials and structures arena, in large part because of the complexities and uncertainties inherent to materials and the structural dynamics of complex systems. It is an area that has received—and continues to receive—significant focus among academics and laboratory researchers [e.g., 208, 209]. One measure of controller performance is robustness. Robustness implies that the closed-loop stability and performance of the control system are insensitive to uncertainties stemming from modeling errors, nonlinearity, unmodeled dynamics, measurement errors, and other unknown disturbances. The more able a control system is to handle these uncertainties, the more robust it is considered to be. Inadequacy of the modeling capabilities certainly increases the degree of difficulty in achieving structural control. The complex behavior of the actuator materials, for example, presents a particularly difficult theoretical problem that may require development of new nonlinear control theories and algorithms.

The selection of the control approach is not straightforward. A significant problem lies in the control of large numbers of sensors and actuators, desirable for reasons of wide-band, spatially distributed structural control, redundancy, and robustness. Rapid, real-time computational capability at high bandwidth is believed to be required to satisfy structural control objectives—mapping sensor outputs into actuator inputs in real time. The computational complexity is substantial, and communication bottlenecks are expected. Current hardware limitations also prevent full interconnection of all the

devices. Control of these large device networks and the associated information management needs may, therefore, require development of new control approaches, such as hierarchical control schemes, NN schemes, or fuzzy logic controllers. While all are in development, none have been experimentally validated in complex systems to any substantial degree. SRI International developed a hierarchical control methodology to address the kilo-input/kilo-output problem in a DARPA-sponsored effort [210]. Their technical approach was based on the wavelet transform, commonly used in signal processing and numerical analysis [e.g., 211]. It is akin to a Fourier transform except that it is decomposed into time and scale rather than frequency. Figure IV-14 schematically illustrates a vibrating surface using this scaling approach. The pyramids above the surface are projections of a virtual surface at coarser and coarser scales (in this way, every device is connected to every other device, although not directly). In essence, data points are being thrown away as one moves away from the surface. Control can actually be implemented at any of these virtual surfaces—one way to get around the issue of local vs. global control. This computationally efficient processing scheme also provides a method for device selection and placement. A particular advantage of this approach is that it does not require optimization of placement of a small number of devices—a challenge when broadband control is desired.

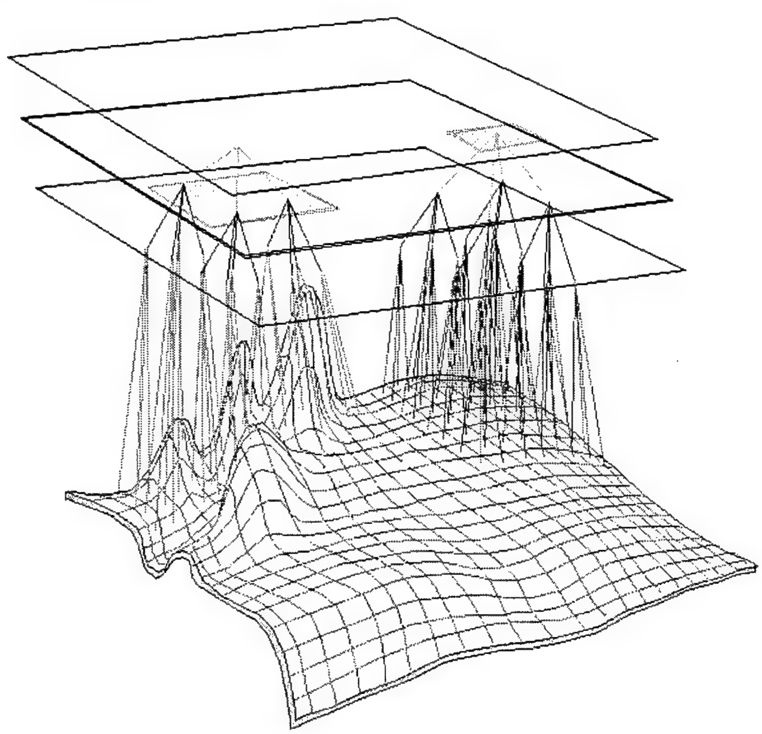

Figure IV-14. Schematic of Hierarchical Control Methodology To Address the Kilo-Input/Kilo-Output Control Problem (Courtesy of SRI International)

An NN is a data processing scheme in which processing elements are fully interconnected [e.g., 212]. Each processing element can receive data from many sources, but these data can only be sent out in one direction. The output can branch with other connections, but each one would carry a signal based on the particular NN interpolating algorithm. Typically, each input is weighted, and all the weighted inputs are summed. The weighting factors are adjusted by the NN during "training" to minimize the errors between the desired output and the NN output. These systems are not programmed but actually learn by training. The quality of the examples used in training determines how well or efficiently the network will perform. The primary advantage of an NN is the potential for orders-of-magnitude-faster computational speed. Of the several types of NN architectures, multilayer back-error propagation is the most common.[43] These types of NNs are suitable for nonlinear control problems, such as system identification (the first step in design and implementation of active controllers) [e.g., 213], damage detection [e.g., 214], and vibration control [e.g., 215].

A fuzzy logic controller is regarded as a set of heuristic (experience- or knowledge-based) decision rules that can be implemented on a computer [e.g., 216]. Such control approaches are of interest to the smart structures community primarily because the control system can be designed without complete analytical knowledge of the structural system. It is believed that these control systems will be quite stable, reliable, and robust. They also allow for adaptive control to suit changing needs. The major issue in designing these systems is determining/selecting the appropriate rules. Geng et al. [217] have combined the fuzzy logic approach with an NN scheme, Fuzzy Cerebellar Model Arithmetic Computer (FCMAC), to allow for an adaptive, self-learning control system. Combining the two approaches offers the advantages of both, apparently without too much loss in performance (e.g., the ability to learn and handle nonlinear behavior, rapid multiple input/output responses, and no need for complete, detailed analytical models). The FCMAC controller hardware, MDSP-100, was successfully designed, built, and tested for controlling a magnetostrictive actuator to demonstrate active vibration isolation of a hexapod (Stewart platform).

One interesting technique, Vibration Control by Confinement™, or VCC™ was developed by QRDC, Inc., under DARPA SBIR funding [e.g., 218]. This approach takes advantage of the phenomenon of modal energy localization (i.e., geometric or material

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43 "Multilayer" refers to a feed-forward arrangement, while "back-propagation" refers to the method by which the NN is trained.

property variations in a structure can result in vibrations concentrated in particular locations of the structure). This is observed most often in rotating and periodic structures but it can occur in all structures under the right conditions. By redirecting energy to noncritical parts of the structure, vibration in critical areas can be reduced. This energy redirection can be achieved passively, through design, or actively via the use of a sensor/actuator/controller network. This approach yields simpler control systems. Instead of having to control the whole structure, one only needs to control selected regions. The approach has been demonstrated successfully on relatively simple structures and is being applied in several more complex demonstrations.

Much of the university research in the area of smart structure control is focused on control of a few modes—using more conventional linear control approaches—in simple structures, such as beams and plates with just a few sensors and actuators. Some of the more complex demonstration structures are being used to evaluate the effectiveness of a variety of control laws. For example, 28 different control laws were evaluated in the series of tests on the PARTI wing [83]. The best was a linear quadratic Gaussian form using single input/single output with a strain gage for feedback along with all 15 piezoceramic actuator groups operating. Even so, efforts to assess the state of control technology for more complex systems using smart materials and structures are inadequate.

F. ELECTRONICS

Of primary concern in the area of electronics are the large size, weight, and high power requirements, particularly for ancillary support equipment (e.g., processors, amplifiers, cabling). Miniaturization of electronics devices will be a critical step forward in addressing this problem. The Air Force and BMDO supported work at TRW on a modular control patch (MCP) [e.g., 37]. The MCP, a 1-in. by 2-in. MCM patch, provided retrofittable, miniaturized diagnostic and control electronics for vibration sensors and actuators. This patch integrated all the necessary features into a single, small, lightweight, low power—but reasonably capable—package that could be embedded in or attached to a structure. An individual patch can be used in a local manner at a discrete location or in concert with a network of other patches in a global manner. A device similar to this was actually used to control embedded piezoceramic actuators in the yoke of a solar array structure to demonstrate vibration-suppression capabilities [219]. The researchers noted a thermal dissipation issue with the electronics, particularly since composites may act as a thermal insulator.

DARPA supported the development of high-frequency switching amplifiers for use with electrostrictive "chiplet" actuator arrays [e.g., 220]. The ultimate goal of this Virginia Tech/Virginia Power Technologies effort was to miniaturize these devices so they could be embedded into the structure with the actuators. This high efficiency amplifier was specifically designed for the capacitive loads that the small, "chiplet" actuators present to it (see Figure IV-15). These are high-efficiency devices. The measured efficiency is about 90 percent at 0.5 kHz, with a decrease down to about 20 percent at 40 kHz.

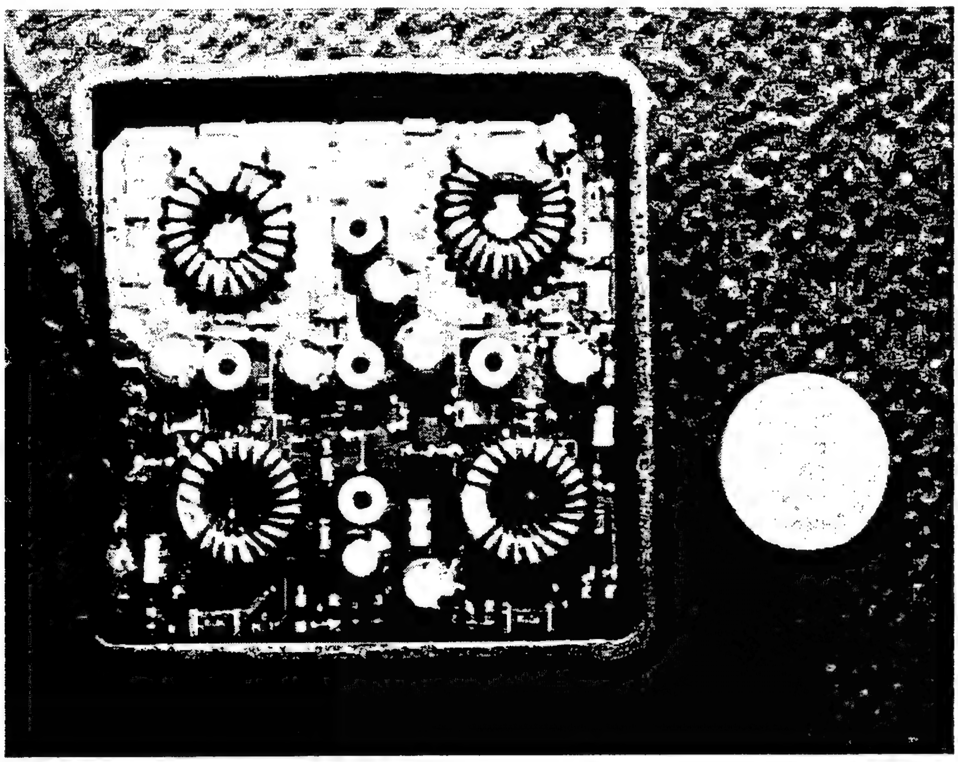

Figure IV-15. Miniature High-Efficiency Power Supply and Amplifiers (Courtesy of Virginia Tech and Virginia Power Technologies)

Another important feature could be the development of small, lightweight power supplies that can be placed with the appropriate electronics for local control. For example, researchers at the Air Force's Rome Laboratory and at Johns Hopkins University (JHU) have developed an all-plastic battery using polymers for electrode materials [e.g., 221]. These batteries, useful in a wide variety of applications, can be recharged hundreds of times and can operate under extreme conditions without serious performance degradation. The finished cells can be as thin as a business card and are malleable so they can be cut to fit. Specific energy densities of 30 to 75 W-hrs/kg are thought possible with these batteries.

Researchers at PSU have examined innovative antennas for use in smart skins. Specifically, barium strontium titanate (BST) materials are being examined for use as a tunable substrate in microwave phase shifters. The dielectric constant of these materials can be changed more than 50 percent by varying the composition and changing the applied bias voltage. Recent results [222] indicate that varying the applied DC voltage can change the operating frequency of the antenna, and incorporating BST phase shifters in the antenna array can provide electronic steerability. These researchers were also combining these antenna concepts with advanced polymer materials and MEMS to develop a wireless telemetry system [223, 224].

G. SYSTEM INTEGRATION

Now that the status and issues associated with the core technologies necessary to achieve truly smart structures—from a hardware perspective—have been described, putting them in the context of a total system is critical.

To assess technology readiness for introduction into aircraft systems, Lincoln [225] has identified five factors necessary to transition structural technologies from the laboratory to full-scale development and deployment:

1. Stabilized materials and material processes
2. Producibility
3. Well-characterized mechanical properties
4. Predictability of structural performance
5. Supportability (i.e., the ability to repair the structure in the field and inspect the structure during manufacturing and service).

Veitch [226] includes additional factors that are also relevant to the introduction of smart materials and structures technologies into air and space structures:

- Availability of characterized materials
- Favorable design trades and cost studies
- Demonstrated affordability
- Development of quality assurance procedures.

A deficiency in any one of these factors may block the transition of the technology.

Many smart material properties are not well known or documented. These materials are not standardized nor are they available "off-the-shelf." Such information needs to be well documented for designers to know how to apply the materials to specific

design applications. This situation reflects the maturity of the field, and time will be required to build up this information. Sometimes, a particular company generates such material property and design data, but this property/data become a part of their proprietary technology.

Better understanding of how the adaptive materials behave under combined electrical, thermal, and mechanical loading is still needed. Power electronics design, transducer design, and actuator system component designs will depend greatly on understanding the material's cross-coupling behavior. More important, perhaps, are the material models that incorporate those effects. These material effects are not easy to implement in component and system design.

For several years, researchers have touted the performance of new solid-state actuators, with each new material and actuator concept showing mostly incremental improvements in capabilities. This performance-driven competition spawned some novel concepts and provided the solid-state actuator community with a beneficial competitive environment. Unfortunately, until recently, other desirable characteristics of actuators, including weight, cost, reliability, and serviceability, have been downplayed. This, in turn, has led to a slow acceptance of solid-state actuators by designers, primarily because of real and perceived negative impacts on system weight, cost, and reliability. While these are considered secondary characteristics by some researchers, they are, in fact, first-order considerations for system designers. Hence, to increase the acceptability of solid-state actuator technology, the performance benefits for systems that include integrated actuators must be balanced against resource impacts and system reliability.

Power, mass, and cost are among the designer's primary considerations. Available electrical power is an especially important design consideration. Strain actuation devices are usually controlled electrically, even though the actuator response may be caused by an electric, magnetic, or thermal field. For command and control (C2), the actuators are integrated into an electronic circuit that also requires power, weight, and, perhaps, hardware and software interfaces with the system computer. While the electrical power needed by a few actuators may be small, highly distributed actuators can require significant system power because of low electrical-to-mechanical energy conversion. Thus, electrical power consumption continues to be a major resource consideration for many applications.

Another feature of smart structures with serious system-level ramifications is the mass of the actuators. FE strain actuation materials often contain lead so that the

actuators are usually more dense than the host structure. To offset the actuator mass, redesign of the host structure incorporating the performance benefits of active structural control can usually result in a neutral or beneficial effect on total system mass. However, simply bonding strain actuators onto the nominal host structure will always increase mass. It is more desirable to redesign the structural component with embedded actuators to take advantage of active strain actuation in reducing the system mass.

Perhaps the most important factor that the designer must manage is cost. Implementation of smart materials and structures technology into commercial products, particularly adaptive structures technologies, suffers from the problem that, in most cases, applying this technology will make the structural subsystem more expensive rather than less expensive. Most customers are primarily, and often only, interested in lowering costs. To date, the focus on cost reduction of all the materials and components of a smart system has not been sufficient. Smart material-based transducers cost too much and require long lead times for delivery. The raw material costs are usually high, but the processing and fabrication costs can be much higher. Because these components are usually produced in small quantities using labor-intensive processes, the device costs are typically high. For example, conventional piezo-stacks are literally laid up by hand. A stack 4 in. tall and 0.75 in. diameter can cost more than $3,000 and will require 12 weeks for delivery. Better manufacturing methods will be required for cost reduction and for product performance repeatability. Economic incentives to apply smart materials and structures technology need to be created. One strategy that will provide large incentives is to use approaches that enable highly capable, multirole vehicles to replace two or more systems.

New materials and new material forms that will be required for many applications are still in laboratory development. Until these materials are in production, the costs will remain high, and their availability will be restricted. For example, the materials for the IDE/PFC active twist concept are prohibitively expensive at this point, although, in time, progress in manufacturing techniques and product quality will lower the cost substantially.

There is a general need to have more and higher volume manufacturers of smart materials and devices to make them cost effective to consider in commercial and industrial products. Cost analyses must be done at the system or system-of-systems level. In addition, there is also a need to develop better, low-cost integration methods to allow for the practical implementation of smart materials systems in high-volume products.

The electronics used for power and C2 also add expense since they are typically customized for a given application. Actuator and electronics parameters should be standardized where possible so that large-scale manufacturing techniques/methods can be employed to reduce the price of these advanced actuation systems.

Next, the designer considers reliability and, sometimes, serviceability. Any product will have to show an acceptable level of fail-safe operation and robustness. For some applications reliability of a smart materials subsystem must be very high since smart material/device failure could result in system failure. On the other hand, in some applications system performance may degrade yet be marginally acceptable if some smart devices fail. In this case, lower reliability can be tolerated, particularly if the system can be serviced to repair the smart subsystem. System redundancy and reconfigurability are issues that impact system reliability, but they have not received much attention to date. The processes used to fabricate smart materials components and structures are not well controlled and documented, a fact that has led to uneven quality of devices (especially actuators), variable device performance parameters, and large numbers of actuator failures, even in laboratory environments. Understanding of failure modes and failure models—and standardized test methods—are lacking. Actuator fabrication processes must be documented and controlled to achieve high reliability. The fatigue behavior, potential corrosion problems, etc., cause operational durability and reliability problems. These issues must be addressed both theoretically and experimentally, such as by life testing of the structure. In addition, applications with graceful failure modes should be exploited first to build a database on operational reliability. Such a database could lead to acceptance by the designer to use strain actuation in critical applications.

Finally, the performance of the smart subsystem must meet the demands of the application. Vibration-control requirements for spacecraft are certainly much different than those for vibration control of an aircraft: e.g., spacecraft designs are typically based on stiffness criteria (high modulus), whereas aircraft designs are based on stress criteria (high strain). Although high-strain performance has been and will continue to be a highly desirable characteristic of strain actuators, the development community is encouraged not to ignore other characteristics in their quest for ever higher strain performance.

To assess the level of maturity of various technologies relative to system level factors, a numerical value can be assigned to the systems factors as described via Lincoln [225] in Table IV-2. Based on these criteria, the authors' assessment is that none of the

Table IV-2. Definition of Technology Maturity Levels

Maturity Level	Definition of Maturity Level
1–2	Materials are not available and need development. No complex parts were built. No test data are available.
3–4	Properties are not reproducible. Testing is not complete. No subcomponent or full-scale components have been built. No cost models have been validated with full-scale parts.
5–7	Limited data are available with large error bars. Subcomponents have been built, but testing is incomplete. Full-scale components have been built but not tested to design loads. Cost model validation is incomplete.
8–10	Materials and processes are well characterized. An extensive database is available for different conditions. Reproducible subcomponents and full-scale components have been built and tested to design loads. Cost models have been validated.

demonstrations described in this paper exceed a Level 5 maturity.[44] Even in cases where full-scale components have been built, they have not been tested to full design loads nor have cost validation models been completed. In some advanced applications, such as the IDE/AFC, the maturity level does not exceed Level 1 or 2. Most other technologies are somewhere in between.

44 An assessment of whether a particular technology meets a given maturity level is somewhat subjective and varies from individual to individual. The system designer is the ultimate authority.

V. CONCLUDING REMARKS

Smart materials and structures are those that can sense external stimuli and respond with active control to that stimulus in real or near-real time. The numerous system demonstrations recently completed or currently underway indicate that smart technologies will likely provide new and innovative capabilities in future commercial and military aerospace systems: spacecraft and launch vehicles; aircraft, including fighter and transport aircraft and UAVs; and helicopters and tilt rotorcraft. Expected benefits include "maintenance on demand," increased passenger/crew comfort, increased system/ component structural life, improved precision pointing and/or sensing capabilities, enhanced aircraft and rotorcraft handling, improved aerodynamics and, possibly, new flight profiles, improved LO characteristics, and reduced manufacturing and assembly costs.

Good progress is being made in the development of appropriate electronics, control approaches, and analysis techniques, although some issues must still be resolved. More work is needed to develop fabrication techniques to make these smart structural systems affordable. Concurrent with that is a need for increased emphasis on integrated system design. Realizing many of the envisioned applications will depend critically upon the development of higher authority, solid-state actuators. Recent discoveries in actuator materials indicate that such substantial improvements are possible, thus broadening the potential for successful implementation.

GLOSSARY

3-D	three-dimensional
AAW	Active Aeroelastic Wing
ACESA	Advanced Composites with Embedded Sensors and Actuators
ACROBAT	Actively Controlled Response Of Buffet-Affected Tails
ACTEX	Active Controls Technology EXperiment
ACX	Active Controls eXperts, Inc.
ADI	Active Damage Interrogation
AE	acoustic emission
AFC	Active Fiber Composite
AFE	anti-ferroelectric
AFRL	Air Force Research Laboratory
AM	amplitude modulation
AMRL	Aeronautics and Maritime Research Laboratory
ARES	Aeroelastic Rotor Experimental System
ARL	Army Research Laboratory
ARL	Applied Research Laboratory (PSU)
ARO	Army Research Office
ASAC	Active Structural Acoustic Control
ASTREX	Advanced Space Structures Technology Research Experiment (Phillips Laboratory)
ATDS	Advanced Technology Demonstration Spacecraft
AVT	Active Vertical Tail
BMDO	Ballistic Missile Defense Organization
BST	barium strontium titanate
BVI	blade-vortex interaction
C2	command and control
CLAS	Conformal Load-Bearing Antenna Structures
CNI	communications, navigation, and identification

CRP	Central Research Project
DAP	directionally attached piezoelectric
DARPA	Defense Advanced Research Projects Agency
DC	direct current
DC–XA	Delta Clipper–eXperimental Advanced
DEW	directed energy weapon
DLR	Deutsche Forschungsanstalt Für Luft-Und Raumfhart
DoD	Department of Defense
DS-1	Deep Space-1
DS-2	Deep Space-2
DSTO	Defence Science and Technology Organization (Australia)
EADS	European Aeronautic Defence and Space Company
EMI	electromagnetic interaction
EW	electronic warfare
FCMAC	Fuzzy Cerebellar Model Arithmetic Computer
FE	ferroelectric
FM	frequency modulation
FTR	Future Technology Rotor
GPS	Global Positioning System
IBC	individual blade control
IDA	Institute for Defense Analyses
IDE–PFC	InterDigitated Electrode–Piezoelectric Fiber Composite
IFOSTP	International Follow-On Structural Testing Project
ISAC	Interaction of Structures, Aerodynamics, and Controls Code
JDIS	Joint Distributed Information System
JHU	Johns Hopkins University
JPL	Jet Propulsion Laboratory
JSF	Joint Strike Fighter
L/D	lift-to-drag
LFN	low-force nut
LFSAH	Lightweight Flexible Solar Array Hinge
LiBaCore	lithium battery core

$LiNBO_3$	lithium niobate
LO	low observable
MACE I	Middeck Active Control Experiment
MAV	micro-air vehicle
MCM	multi-chip module
MCP	modular control patch
MEMS	microelectromechanical systems
MIT	Massachusetts Institute of Technology
MVIS	Miniature Vibration Isolation System
NACA	National Advisory Committee on Aeronautics
NASA	National Aeronautics and Space Administration
NMP	New Millennium Program (NASA)
NN	neural network
NRL	Naval Research Laboratory
O&S	operating and support
ONR	Office of Naval Research
OSP	Orbital/Suborbital Program
PARTI	Piezoelectric Aeroelastic Response Tailoring Investigation
PETRA	PiezoElectric Twist Rotor Analysis
PHM	Prognostics and Health Management
PLSnZT	lead-lanthanate-stannate-zirconate-titanate
PLZT	piezoceramic lead-lanthanate-zirconate-titanate
PMN	lead magnesium niobate
PMN–PT	lead magnesium niobate–lead titanate
PSU	Pennsylvania State University
PVDF	polyvinylidene difluoride
PZT	piezoelectric lead-zirconate-titanate
RAINBOW	Reduced And INternally Biased Oxide Wafers
RCS	radar cross section
RF	radio frequency
RLV	reusable launch vehicle
RMS	root mean square

RQEM	Remotely Queried Embedded Microsensor
RTM	resin transfer molding
S^3TD	Smart Skin Structures Technology Demonstration
SAMPSON	Smart Aircraft and Marine Propulsion System demONstration
SBIR	Small Business Innovative Research
SBR	space-based radar
SDIO	Strategic Defense Initiative Organization
SIES	Spacecraft Integrated Electronic Structure
SIMS	Structural Integrity Monitoring System
SMA	shape memory alloy
SMARD	Shape Memory Actuation Release Devices
SMART	Smart Materials Actuated Rotor Technology
SPICES	Synthesis and Processing of Intelligent, Cost-Effective Structures
SRA	Systems Research Aircraft (NASA-Dryden)
SSRC	Smart Structures for Rotorcraft Control
STRV-2	Space Test Research Vehicle-2
TDT	Transonic Dynamics Tunnel
THUNDER	THin layer UNimorph DrivER
TSN	two-stage nut
TTCP	The Technical Cooperation Program
UAV	unmanned air vehicle
UCAV	Unmanned Combat Air Vehicle
UCLA	University of California at Los Angeles
UHF	ultrahigh frequency
VCC™	Vibration Control by Confinement™
VHF	very high frequency
VISS	Vibration Isolation and Suppression System

REFERENCES

1. Clauser, H.R., "Modern Materials Concepts Make Structure Key to Progress," *Materials Engineering*, Vol. 68, No. 6, November 1968, pp. 38–42.

2. Clauser, H.R., "From Static to Dynamic Materials in Design," *Mechanical Engineering*, May 1975, pp. 20–26.

3. Forward, R.L., "Electromechanical Transducer-Coupled Mechanical Structure With Negative Capacitance Compensation Circuit," U.S. Patent 4,158,787, June 19, 1979.

4. Forward, R.L., and R.W. Peterson, "Cold Damping of Mechanical Structures," U.S. Patent 4,199,989, April 29, 1980.

5. Forward, R.L, "Apparatus and Method for Electronic Damping of Resonances," U.S. Patent 4,352,481, October 5, 1982.

6. Forward, R.L., C.J. Swigert, and M. Obal, "Electronic Damping of a Large Optical Bench," *The Shock and Vibration Bulletin, Part 4 Damping and Machinery Dynamics*, Bulletin 53, May 1983, pp. 51–61.

7. Ikegami, R., D.G. Wilson, and J.H. Laakso, "Advanced Composites With Embedded Sensors and Actuators (ACESA)," Final Report AL-TR-90-022, Astronautics Laboratory/Air Force Space Technology Center, June 1990, 111 pages.

8. Bronowicki, A.J., T.L. Mendenhall, and R.M. Manning, "Advanced Composites With Embedded Sensors and Actuators (ACESA)," Final Report AL-TR-89-086, Astronautics Laboratory/Air Force Space Technology Center, April 1990, 150 pages.

9. Bronowicki, A.J., R.S. Betros, G.R. Dvorsky, R.E. Wyse, J.W. Innis, and S.P. Kuritz, "Advanced Composites With Embedded Sensors and Actuators (ACESA)," Phase III–V Final Report, PL-TR-93-3017, Phillips Laboratory Space & Missiles Directorate, Kirtland AFB, November 1993, 72 pages.

10. Wada, B.K., J.I. Fanson, and E.F. Crawley, "Adaptive Structures," *Journal of Intelligent Material Systems and Structures*, Vol. 1, April 1990, pp. 157–174.

11. Matsuzaki, Y., and B.K. Wada, Eds., *Second Joint Japan/U.S. Conference on Adaptive Structures*, Technomic Publishing Co., Inc., Lancaster, PA, 1992, 885 pages.

12. Loewy, R.G, "Recent Developments in Smart Structures With Aeronautical Applications," *Smart Materials and Structures*, Vol. 6, 1997, pp. R11–R42.

13. DeCamp, R.W., R. Hardy, and D.K. Gould, "Mission-Adaptive Wing," *Proceedings of the SAE International Pacific Air and Space Technology Conference*, SAE-87-2419, Vol. A89-10627 01-01, Society of Automotive Engineers, Warrendale, PA, 1987, pp. 189–195.

14. Powers, S.G., and L.D. Webb, "Flight Wing Surface Pressure and Boundary-Layer Data Report From the F-111," NASA-Dryden Flight Research Center, Edwards, CA, Report Number: NASA-TM-4789.

15. Hall, J.M., "Executive Summary AFTI/F-111 Mission Adaptive Wing," WRDC-TR-89-3083, Wright Patterson AFB, OH, September 1989.

16. Wong, K.J., "AFTI/F-111 Mission Adaptive Wing Lift and Drag Flight Test Results," AFFTC-TR-86-42, Final Report, March 1987.

17. Kudva, J.N, A.J. Lockyer, and C.B. Van Way, "Structural Health Monitoring of Aircraft Components," *AGARD Lecture Series 205, Smart Structures and Materials: Implications for Military Aircraft of New Generation*, Paper 9, October 1996, pp. 9-1–9-6.

18. Scheuren, W.J., K.A. Caldwell, G.A. Goodman, and A.K. Wegman, "Joint Strike Fighter Prognostics & Health Management," *Proceedings of the International Powered Lift Conference*, Royal Aeronautical Society, London, UK, 1998, pp. 38.1–38.7.

19. Fedele, P., G. Cafasso, and L. Leece, "A New Technique for Damage Identification and Health Monitoring of Structures Using Piezoelectric Sensors and Actuators," *7th International Conference on Adaptive Structures*, Technomic Publishing Co., Inc., Lancaster, PA, 1997, pp. 232–242.

20. Concillio, A., L. and Leece, "A Survey on Italian Activities in Smart Structures," presented at *Engineered Adaptive Structures for Noise Control and Vibration Control II* (Castelvecchio, Italy, 16–21 May 1999), Engineering Foundation, New York, NY, 1999.

21. Van Way, C.B., J.N. Kudva, M.L. Ziegler, J.M. Alper, M.N. West, and T.G. Edwards, "Development of an Automated Aircraft Structural Integrity Monitoring System—Overview of the Air Force/Navy Smart Metallic Structures Program," *Proceedings of the 37th Structures, Structural Dynamics, and Materials Conference*, AIAA-96-1615-CP, AIAA, Reston, VA, April 1996.

22. Kudva, J.N., M.J. Grage, and M.M. Roberts, "Aircraft Structural Health Monitoring and Other Smart Structures Technologies—Perspectives on Development of Future Smart Aircraft," in publication.

23. Kudva, J.N., C. Marantidis, J. Gentry, and E. Blazic, "Smart Structures Concepts for Aircraft Structural Health Monitoring," *Smart Structures and Intelligent Systems*, Paper 1917-92, Vol. 1917, Society of PhotoOptical Instrumentation Engineers (SPIE), Bellingham, WA, 1993.

24. Van Way, C.B., et al., "Integration of Smart Structures Concepts for Improved Structural Integrity Monitoring of the T-38 Aircraft," *Proceedings of the USAF ASIP Conference*, San Antonio, TX, December 1993.

25. Gentry, J.D., et al., "The Impact of Smart Structures on Aircraft Structural Integrity Programs," *Proceedings of the 1992 USAF Aircraft Structural Integrity Program Conference*, San Antonio, TX, December 1992.

26. Lichtenwalner, P., J.P. Dunne, R.S. Becker, and E.R. Baumann, "Active Damage Interrogation System for Structural Health Monitoring," *Industrial and Commercial Applications of Smart Structures Technologies*, Vol. 3044, Society of PhotoOptical Instrumentation Engineers (SPIE), Bellingham, WA, 1997, pp. 186–194.

27. Obermeier, E., and B. Haslam, "Eurofighter Technology for the 21st Century," *Proceedings of the 21st ICAS Congress*, ICAS Paper 98-04, AIAA, Reston, VA, September 1998, 10 pages.

28. Hunt, S.R., and I.G. Hebden, "Eurofighter 2000: An Integrated Approach to Structural Health Monitoring," *Proceedings 19th ICAF Symposium: Fatigue In New and Aging Aircraft*, Cradley Health Engineering Materials Advisory Services, Ltd., UK, 1997, pp. 481–498.

29. Kiefer, K., "Applications of Wireless Data Acquisition and Control Techniques," presented at *Engineered Adaptive Structures for Noise Control and Vibration Control II* (Castelvecchio, Italy, 16–21 May 1999), Engineering Foundation, New York, NY, 1999.

30. Krantz, D., J. Belk, P.J. Biermann, J. Dubow, L.W. Gause, R. Harjani, S. Mantell, D. Polla, and P. Troyk, "Project Update: Applied Research on Remotely Queried Embedded Microsensors," *Smart Electronics and MEMS*, Vol. 3328, Society of PhotoOptical Instrumentation Engineers (SPIE), Bellingham, WA, 1999, pp. 124–132.

31. Baumann, E.R., R.S. Becker, P.J. Ellerbrock, and S.W. Jacobs, "DC–XA Structural Health Monitoring," *Industrial and Commercial Applications of Smart Structures Technologies*, Vol. 3044, Society of PhotoOptical Instrumentation Engineers (SPIE), Bellingham, WA, 1997, pp. 195–206.

32. Ellerbrock, P.J., "DC–XA Structural Health Monitoring Fiber Optic-Based Strain Measurement System," *Industrial and Commercial Applications of Smart Structures Technologies*, Vol. 3044, Society of PhotoOptical Instrumentation Engineers (SPIE), Bellingham, WA, 1997, pp. 206–218.

33. Miller, D., et al., "The Middeck Active Control Experiment (MACE): Summary Report," MIT Space Engineering Research Center, SERC Report #7–96, Massachusetts Institute of Technology, Cambridge, MA, June 1996.

34. Davis, L.D., and D.C. Hyland, "Adaptive Neural Control for Space Structure Vibration Suppression," Technical Report, PL-TR-96-1133, Phillips Laboratory Space & Missiles Directorate, Kirtland AFB, August 1996.

35. Denoyer, K.K., and R.R. Ninneman, "Increasing Autonomy of Spacecraft Using Neural Network Adaptive Control," *Proceedings of the Space Technology and Applications International Forum 1999*, Albuquerque, NM, February 1999, pp. 636–641.

36. Manning, R.A., and C.N. Foley, "Identification of Experiment Dynamics and Environmental Effects on the ACTEX I Flight Experiment," *Proceedings of the AIAA Guidance, Dynamics, and Controls Conference*, AIAA-99-3591, AIAA, Reston, VA, 1999.

37. Obal, M., and J.M. Sater, "Multi-Functional Structures: The Future of Spacecraft Design?," *5th International Conference on Adaptive Structures*, Technomic Publishing Co., Inc., Lancaster, PA, 1995, pp. 720–734.

38. Cobb, R.G., J.M. Sullivan, A. Das, L.P. Davis, T.T. Hyde, T. Davis, Z.H. Rahman, and J.T. Spanos, "Vibration Isolation and Suppression System for Precision Payloads in Space," *Smart Materials and Structures*, Vol. 8, 1999, pp. 1–15.

39. Sciulli, D., and S.F. Griffin, "Hybrid Launch Isolation System," *Industrial and Commercial Applications of Smart Structures Technologies*, SPIE 3674-40, Vol. 3674, Society of PhotoOptical Instrumentation Engineers (SPIE), Bellingham, WA, 1999, pp. 352–359.

40. Wilke, P.S., C.D. Johnson, and P.J. Grosserode, "GFO/Taurus Whole Spacecraft Isolation System," *Proceedings of the 12th AIAA/USU Conference on Small Satellites*, SSC-98-III-1, AIAA, Reston, VA, September 1998.

41. Carpenter, B.F., C. Clark, and W. Weems, "Shape Memory Actuated Release Mechanisms," *Industrial and Commercial Applications of Smart Structures Technologies*, Paper 2721-31, Vol. 2721, Society of PhotoOptical Instrumentation Engineers (SPIE), Bellingham, WA, 1996, pp. 420–426.

42. Private communication with Dr. Suraj Rawal, Lockheed Martin Astronautics, July 31, 1999.

43. Fuller, C.R., and A.H. Von Flotow, "Active Control of Sound and Vibration," *IEEE Control Systems*, December 1995, pp. 9–19.

44. Lyle, K.H., and R.J. Silcox, "A Study of Active Trim Panels for Noise Reduction in an Aircraft Fuselage," *General, Corporate and Regional Aviation Meeting and Exposition*, Paper SAE-95-1179, Society of Automotive Engineers, Warrendale, PA, 1995.

45. Silcox, R.J., H.C. Lester, and T.J. Coats, "An Analytical Study of Intensity Flow for Active Structural Acoustic Control," *Proceedings of the SAE Noise and Vibration Conference*, SAE-93-1284, Society of Automotive Engineers, Warrendale, PA, 1993.

46. Ruckman, C.E., and C.R. Fuller, "Optimizing Actuator Locations in Active Noise Control Systems Using Subset Selection," *Journal of Sound and Vibration*, Vol. 186, No. 3, September 1995, pp. 395–406.

47. Padula, S.L., and R.K. Kincaid, "Aerospace Applications of Integer and Combinatorial Optimization," NASA TM-110210, NASA-Langley Research Center, Hampton, VA, October 1995.

48. Hirsch, S.M., V. Jayachandran, and J.Q. Sunn, "Structural-Acoustic Control for Quieter Aircraft Interior—Smart Trim Technology," *Composite Structures*, Vol. 42, 1998, pp. 189–202.

49. Fuller, C.R., C. Guigou, and C.A. Gentry, "Foam-PVDF Smart Skin for Active Control of Sound," *Industrial and Commercial Applications of Smart Structures Technologies*, Vol. 2721, Society of PhotoOptical Instrumentation Engineers (SPIE), Bellingham, WA, 1996, pp. 26–37.

50. Sollo, A., L. Leece, V. Guaranta, N. Doelman, and E. Doppenberg, "Active Noise Control on ATR Fuselage Mock-Up by Piezoceramic Actuators," *Proceedings of the AIAA/CEAS Aeroacoustics Conference, 4th*, AIAA-98-2230, AIAA, Reston, VA, 1998, pp. 174–183.

51. Leece, L., and M. Viscardi, "Active Control of Cabin Noise," presented at *Engineered Adaptive Structures for Noise Control and Vibration Control II* (Castelvecchio, Italy, 16–21 May 1999), Engineering Foundation, New York, NY, 1999.

52. Kincaid, R.K., and S.L. Padula, "Quelling Cabin Noise in Turboprop Aircraft via Active Control," *Journal of Combinatorial Optimization*, Vol. 1, 1997, pp. 229–250.

53. Mathur, G., B. Tran, and M. Simpson, "Broadband Active Structural Acoustic Control of Aircraft Cabin Noise—Lab Tests," *AIAA/CEAS 3rd Aeroacoustics Conference*, AIAA-97-1636, AIAA, Reston, VA, May 1997.

54. Cruz, J.D., "Active Suppression of Aircraft Panel Vibration With Piezoceramic Strain Actuators," *Journal of Aircraft*, Vol. 35, No. 1, 1998, pp. 139–144.

55. Larson, C.R., J.S. Rosenthal, R.R. Neurgoankar, E. Falangas, J.G. Nelson, S.K. Dobbs, C.L. Hustedde, and S.F. McGrath, "Piezoceramic Active Vibration Suppression Flight Demonstration Program on the B-1B Aircraft," *Proceedings of the 39th Structures, Structural Dynamics and Materials Conference*, AIAA-98-1926, AIAA, Reston, VA, 1998, pp. 1847–1856.

56. Larson, C.R., E. Falangas, S.K. Dobbs, R.R. Neurgoankar, J.G., Nelson, J.S. Rosenthal, C.L. Hustedde, and S.F. McGrath, "Piezoceramic Active Vibration Suppression Control System Development for the B-1B Aircraft," *Industrial and Commercial Applications of Smart Structures Technologies*, Vol. 3326, Society of PhotoOptical Instrumentation Engineers (SPIE), Bellingham, WA, 1998, pp. 294–305.

57. Finn, E.D., "Lowering the Volume on Helicopters," *Aerospace America*, January 1997, pp. 24–25.

58. Moses, R.W., "Contributions to Active Buffeting Alleviation Programs by the NASA Langley Research Center," *Proceedings of the 40th Structures, Structural Dynamics, and Materials Conference*, AIAA-99-1318, AIAA, Reston, VA, 1999.

59. Ryall, T.G., R.W. Moses, M.A. Hopkins, D. Henderson, D.G. Zimcik, and F. Nitzsche, "Buffet Load Alleviation," *Proceedings of the Second Australasian Congress on Applied Mechanics*, Paper R-017, Canberra, Australia, 1999, pp. 126–131.

60. Moses, R.W., "Vertical Tail Buffet Alleviation Using Piezoelectric Actuators—Some Results of the Actively Controlled Response of Buffet-Affected Tails (ACROBAT) Program," *Industrial and Commercial Applications of Smart Structures Technologies*, Vol. 3044, Society of PhotoOptical Instrumentation Engineers (SPIE), Bellingham, WA, 1997, pp. 87–98.

61. Zimmerman, N.H., and M.A. Ferman, "Prediction of Tail Buffet Loads for Design Application," Vols. I and II, Report No. NADC-88043-60, July 1987.

62. Lee, B.H.K., D. Brown, M. Zgela, and D. Poirel, "Wind Tunnel Investigation and Flight Tests of Tail Buffet on the CF-18 Aircraft," *Aircraft Dynamic Loads Due to Flow Separation*, N91-14324 06-05, AGARD-CP-483, NATO Advisory Group for Aerospace Research and Development, April 1990.

63. Pettit, C.L., M. Banford, D. Brown, and E. Pendleton, "Pressure Measurements on an F/A-18 Twin Vertical Tail in Buffeting Flow," Volumes 1–4, United States Air Force, Wright Laboratory, TM-94-3039, Wright Patterson AFB, OH, August 1994.

64. Meyn, L.A., and K.D. James, "Full-Scale Wind-Tunnel Studies of F/A-18 Tail Buffet," *Journal of Aircraft*, Vol. 33, No. 3, July 1996, pp. 589–595.

65. Moses, R.W., and E. Pendleton, "A Comparison of Pressure Measurements Between a Full-Scale and a 1/6-Scale F/A-18 Twin Tail During Buffet," *83rd Structures And Materials Panel (SMP) Meeting, Loads and Requirements for Military Aircraft*, AGARD-R-815, NATO Advisory Group for Aerospace Research and Development, September 1996.

66. Ashley, H., S.M. Rock, R. Digumarthi, K. Chaney, and A.J. Eggers, Jr., "Active Control For Fin Buffet Alleviation," WL-TR-93-3099, Air Force Wright Laboratory, Wright Patterson AFB, Dayton, OH, January 1994.

67. Hauch, R.M., J.H. Jacobs, K. Ravindra, and C. Dimas, "Reduction of Vertical Tail Buffet Response Using Active Control," *Proceedings of the 36th Structures, Structural Dynamics, and Materials Conference*, AIAA-95-1080-CP, Part 4, AIAA, Reston, VA, April 1995, pp. 2281–2288.

68. Hauch, R.M., J.H. Jacobs, C. Dima, and K. Ravindra, "Reduction of Vertical Tail Buffet Response Using Active Control," *Journal of Aircraft*, Vol. 33, No. 3, May–June 1996, pp. 617–622.

69. Lazarus, K.B., E. Saarmaa, and G.S. Agnes, "An Active Smart Material System for Buffet Load Alleviation," *Industrial and Commercial Applications of Smart Structures Technologies*, Vol. 2447, Society of PhotoOptical Instrumentation Engineers (SPIE), Bellingham, WA, 1995, pp. 179–192.

70. Hopkins, M., R. Moses, D. Zimcik, D. Henderson, T. Ryall, and R. Spangler, "Active Vibration Suppression Systems Applied to Twin Tail Buffeting," *Industrial and Commercial Applications of Smart Structures Technologies*, Vol. 3326, Society of PhotoOptical Instrumentation Engineers (SPIE), Bellingham, WA, 1998, pp. 27–33.

71. Spangler, R.L., and R.N. Jacques, "Testing of an Active Smart Material System for Buffet Load Alleviation," *Proceedings of the 40th Structures, Structural Dynamics, and Materials Conference*, AIAA-99-1316, AIAA, Reston, VA, 1999, 11 pages.

72. Hanagud, S., M. Bayon de Noyer, H. Lou, D. Henderson, and K.S. Nagaraja, "Tail Buffet Alleviation of High Performance Twin Tail Aircraft Using Piezo-Stack Actuators," *Proceedings of the 40th Structures, Structural Dynamics, and Materials Conference*, AIAA-99-1320, AIAA, Washington, DC, 1999, 11 pages.

73. Thorby, D.C., "Can Piezoelectric Methods Be Used to Control Aircraft Buffet Response?," *CEAS International Forum on Aeroelasticity and Structural Dynamics*, Paper A97-3665A 09-31, Vol. 2, Associazione Italiana di Aeronautica ed Astronautica, Rome, Italy, 1997, pp. 351–358.

74. Simpson, J., and J. Schweiger, "An Industrial Approach to Piezo Electric Damping of Large Fighter Aircraft Components," *Industrial and Commercial Applications of Smart Structures Technologies*, Vol. 3326, Society of PhotoOptical Instrumentation Engineers (SPIE), Bellingham, WA, 1998, pp. 34–46.

75. Becker, J., W. Schröder, K. Dittrich, E. Bauer, and H. Zippold, "The Advanced Aircraft Structures Program—An Overview," *Industrial and Commercial Applications of Smart Structures Technologies*, Vol. 3674, Society of Photo-Optical Instrumentation Engineers (SPIE), Bellingham, WA, 1999, pp. 2–12.

76. Zaglauer, H.W., J.K. Dürr, E. Flöth, E. Ihler, U. Herold-Schmidt, K. Dittrich, J. Simpson, and J. Becker, "Fin-Buffet Alleviation via Distributed Piezoelectric Actuators-Materials Qualification Program," *Industrial and Commercial Applications of Smart Structures Technologies*, Vol. 3674, Society of PhotoOptical Instrumentation Engineers (SPIE), Bellingham, WA, 1999, pp. 22–30.

77. Manser, R., J. Simpson, J. Becker, J.K. Dürr, E. Flöth, U. Herold-Schmidt, H. Stark, and H.W. Zaglauer, "Fin-Buffet Alleviation via Distributed Piezoelectric Actuators—Full Scale Demonstrator Tests," *Industrial and Commercial Applications of Smart Structures Technologies*, Vol. 3674, Society of PhotoOptical Instrumentation Engineers (SPIE), Bellingham, WA, 1999, pp. 13–21.

78. Becker, J., and W. Wolfgang, "Comparison of Piezoelectric Systems and Aerodynamic Systems for Aircraft Vibration Alleviation," *Industrial and Commercial Applications of Smart Structures Technologies*, Vol. 3326, Society of PhotoOptical Instrumentation Engineers (SPIE), Bellingham, WA, 1998, pp. 13–26.

79. Stüwing, M., D. Sachau, and E. Breitbach, "Adaptive Vibration Damping of Fin Structures," *Industrial and Commercial Applications of Smart Structures Technologies*, Vol. 3674, Society of PhotoOptical Instrumentation Engineers (SPIE), Bellingham, WA, 1999, pp. 31–38.

80. Gade, P.V.N., and D.J. Inman, "Two-Dimensional Active Wing/Store Flutter Suppression Using H_∞ Theory," *Journal of Guidance, Control, and Dynamics*, Vol. 20, 1997, pp. 949–955.

81. McGowan, A.R., W.K. Wilkie, R.W. Moses, R.C. Lake, J. Pinkerton-Florance, C.D. Wieseman, M.C. Reaves, B.K. Taleghani, P.H. Mirick, and M.L. Wilbur, "Aeroservoelastic and Structural Dynamics Research on Smart Structures Conducted at NASA Langley Research Center," *Industrial and Commercial Applications of Smart Structures Technologies,* Paper 3326-20, Vol. 3326, Society of PhotoOptical Instrumentation Engineers (SPIE), Bellingham, WA, 1998.

82. Heeg, J., and A. McGowan, "The Piezoelectric Aeroelastic Response Tailoring Investigation: A Status Report," *Industrial and Commercial Applications of Smart Structures Technologies*, Vol. 2447, Society of PhotoOptical Instrumentation Engineers (SPIE), Bellingham, WA, 1995, pp. 2–13.

83. McGowan, A.R., J. Heeg, and R.C. Lake, "Results of Wind-Tunnel Testing From the Piezoelectric Aeroelastic Response Tailoring Investigation," *Proceedings of the 37th Structures, Structural Dynamics, and Materials Conference*, AIAA-96-1511, AIAA, Reston, VA, 1996, 11 pages.

84. "The Langley Transonic Dynamics Tunnel," LWP-799, September 1969.

85. Derham, R.C., and N.W. Hagood, "Rotor Design Using Smart Materials to Actively Twist Blades," *Proceedings of the American Helicopter Society 52nd Annual Forum*, Vol. 2, American Helicopter Society, Alexandria, VA, 1996, pp. 1242–1252.

86. Straub, F.K., and R.J. King, "Application of Smart Materials to Control of a Helicopter Rotor," *Industrial and Commercial Applications of Smart Structures Technologies*, Vol. 2721, Society of PhotoOptical Instrumentation Engineers (SPIE), Bellingham, WA, 1996, pp. 66–76.

87. Mitrovic, M., G.P. Carman, and F. Straub, "Response of Piezoelectric Stack Actuators Under Combined Electro-Mechanical Loading," *International Journal of Solids and Structures*, to be published in 2000.

88. Mitrovic, M., G.P. Carman, and F. Straub, "Durability Characterization of Piezoelectric Stack Actuators Under Combined Electro-Mechanical Loading," *Proceedings of the 41st Structures, Structural Dynamics and Materials Conference*, Paper AIAA-2000-1500, AIAA, Reston, VA, April 2000.

89. Prechtl, E.F., and S.R. Hall, "An X-Frame Actuator Servo-Flap Actuation System for Rotor Control," *Smart Structures and Integrated Systems*, SPIE 3329-33, Vol. 3329, Society of PhotoOptical Instrumentation Engineers (SPIE), Bellingham, WA, 1998.

90. Hall, S.R., and E.F. Prechtl, "Preliminary Testing of a Mach-Scaled Active Rotor Blade With a Trailing Edge Servo-Flap," *Smart Structures and Integrated Systems*, Vol. 3668, Society of PhotoOptical Instrumentation Engineers (SPIE), Bellingham, WA, 1999, pp. 14–21.

91. Prechtl, E.F., and S.R. Hall, "Design of a High Efficiency, Large Stroke, Electromechanical Actuator," *Smart Materials and Structures*, Vol. 8, 1999, pp. 13–30.

92. du Plessis, A., and N. Hagood, "Performance Investigation of Twist Actuated Single Cell Composite Beams for Helicopter Blade Control," *6th International Conference on Adaptive Structures Technology*, Technomic Publishing Co., Inc., Lancaster, PA, 1996, pp. 191–216.

93. Wilkie, W.K., W.K. Belvin, and K.C. Park, "Aeroelastic Analysis of Helicopter Rotor Blades Incorporating Anisotropic Piezoelectric Twist Actuation," *Proceedings of the ASME World Congress and Exposition, Adaptive Structures Symposium*, American Society of Mechanical Engineers, New York, NY, 1996, pp. 423–433.

94. Wilkie, W.K., "Anisotropic Piezoelectric Twist Actuation of Helicopter Rotor Blades: Aeroelastic Analysis and Design Optimization," Ph.D. Dissertation, University of Colorado, Boulder, CO, 1997.

95. Rodgers, J.P., N.W. Hagood, and D.A. Weems, "Design and Manufacture of an Integral Twist-Actuated Rotor Blade," *Proceedings of the 38th Structures, Structural Dynamics and Materials Conference and Adaptive Structures Forum*, Paper AIAA-97-1264, AIAA, Reston, VA, April 1997.

96. Wilkie, W.K., M.L. Wilburn, P.H. Mirick, C.E.S. Cesnik, and S.J. Shin, "Aeroelastic Analysis of the NASA/Army/MIT Active Twist Rotor," American Helicopter Society 55th Annual Forum, Montreal, Canada, May 25–27, 1999.

97. Ham, N., "Helicopter Individual-Blade-Control Research at MIT 1977–1985," *Vertica*, Vol. 11, 1987, pp. 109–122.

98. Ormiston, R.A., "Smart Materials and Structures for Rotor Dynamics Applications," *Proceedings of the 4th ARO Workshop on Smart Structures*, Pennsylvania State University, State College, PA, August 16–18, 1999.

99. Bent, A., N. Hagood, and J. Rodgers, "Anisotropic Actuation With Piezoelectric Fiber Composites," *Journal of Intelligent Material Systems and Structures*, Vol. 6, May 1995, pp. 338–349.

100. Bent, A., and N. Hagood, "Improved Performance in Piezoelectric Fiber Composites Using Interdigitated Electrodes," *Smart Materials*, Vol. 2441, Society of PhotoOptical Instrumentation Engineers (SPIE), Bellingham, WA, February 1995, pp. 196–212.

101. Hagood, N., R. Kindel, K. Ghandi, and P. Gaudenzi, "Improving Transverse Actuation of Piezoceramics Using Interdigitated Surface Electrodes," *Smart Structures and Intelligent Systems*, Vol. 1917, Part 1, Society of PhotoOptical Instrumentation Engineers (SPIE), Bellingham, WA, February 1993, pp. 341–352.

102. Chen, P.C., and I. Chopra, "Hover Testing of Smart Rotor With Induced-Strain Actuation of Blade Twist," *AIAA Journal*, Vol. 35, No. 1, January 1997, pp. 6–16.

103. Bernhard, A.P., and I. Chopra, "Trailing Edge Flap Activated by a Piezo-Induced Bending-Torsion Coupled Beam," *Journal of the American Helicopter Society*, Vol. 44, No. 1, January 1999, pp. 3–15.

104. Koratkar, N., and I. Chopra, "Development of a Smart Rotor With Piezoelectric Bender Actuated Trailing Edge Flaps," *Proceedings of the 4th ARO Workshop on Smart Structures*, Pennsylvania State University, State College, PA, August 16–18, 1999.

105. Yeager, W., P. Mirick, M.N. Hamouda, M. Wilbur, J. Singleton, and W. Keats Wilkie, "Rotorcraft Aeroelastic Testing in the Langley Transonic Dynamics Tunnel," *Journal of the American Helicopter Society*, Vol. 38, No. 3, July 1993, pp. 73–82.

106. Barrett, R.M., and R.S. Gross, "Adaptive Aerostructures Demonstrations of Flightworthy Hardware," *Proceedings of the 4th European Smart Structures and Materials and 2nd Micromechanics, Intelligent Materials and Robotics Conference*, Institute of Physics Publishing, Bristol, UK, 1998, pp. 749–753.

107. Ehlers, S.M., and T.A. Weisshaar, "Static Aeroelastic Behavior of Adaptive Laminated Piezoelectric Composite Wing," *AIAA Journal*, Vol. 28, No. 4, 1990.

108. Barrett, R., "Active Plate and Wing Research Using EDAP Elements," *Journal of Smart Materials and Structures*, Vol. 1, No. 3, pp. 214–226.

109. Barrett, R., R.S. Gross, and F.T. Brozoski, "Design and Testing of Subsonic All-Moving Smart Flight Control Surfaces," *Proceedings of the 36th Structures, Structural Dynamics, and Materials Conference*, AIAA-95-1081, AIAA, Reston, VA, 1995, pp. 2289–2296.

110. Barrett, R., and J. Stutts, "Design and Testing of a 1/12th Scale Solid State Adaptive Rotor," *Journal of Smart Materials and Structures*, Vol. 6, No. 4, 1997, pp. 491–497.

111. Barrett, R., and J. Stutts, "Modeling, Design, and Construction of a Barrel-Launched Adaptive Munition," *Smart Structures and Integrated Systems*, Vol. XXX, Society of PhotoOptical Instrumentation Engineers (SPIE), Bellingham, WA, pp. 578–589.

112. Monner, H.P., H. Hanselka, and E. Breitbach, "Development and Design of Flexible Fowler Flaps for an Adaptive Wing," *Industrial and Commercial Applications of Smart Structures Technologies*, Vol. 3326, Society of PhotoOptical Instrumentation Engineers (SPIE), Bellingham, WA, 1998, pp. 60–70.

113. Kudva, J.N, A.J. Lockyer, and K. Appa, "Adaptive Aircraft Wing," *AGARD Lecture Series 205, Smart Structures and Materials: Implications for Military Aircraft of New Generation*, Paper 10, October 1996, pp. 10-1–10-5.

114. Kudva, J.N., C.A. Martin, L.B. Scherer, A.P. Jardine, A.R. McGowan, R.C. Lake, G. Sendeckyj, and B. Sanders, "Overview of the DARPA/AFRL/NASA Smart Wing Program," *Industrial and Commercial Applications of Smart Structures Technologies*, SPIE 3674-28, Vol. 3674, Society of PhotoOptical Instrumentation Engineers (SPIE), Bellingham, WA, pp. 230–236.

115. Kudva, J., K. Appa, C. Martin, P. Jardine, G. Sendeckyj, T. Harris, A. McGowan, and R. Lake, "Design, Fabrication and Testing of the DARPA/WL Smart Wing Wind-Tunnel Model," *Proceedings of the 38th Structures, Structural Dynamics, and Materials Conference and Adaptive Structures Forum*, AIAA-97-1198, AIAA, Reston, VA, 1997.

116. Martin, C., J. Bartley-Cho, J. Flanagan, and B.F. Carpenter, "Design and Fabrication of Smart Wing Wind Tunnel Model and SMA Control Surfaces," *Industrial and Commercial Applications of Smart Structures Technologies*, SPIE 3674-28, Vol. 3674, Society of PhotoOptical Instrumentation Engineers (SPIE), Bellingham, WA, 1999, pp. 237–248.

117. Jardine, A.P., J. Bartley-Cho, and J. Flanagan, "Improved Design and Performance of the SMA Torque Tube for the DARPA Smart Wing Program," *Industrial and Commercial Applications of Smart Structures Technologies*, SPIE 3674-29, Vol. 3674, Society of PhotoOptical Instrumentation Engineers (SPIE), Bellingham, WA, 1999, pp. 260–269.

118. Scherer, L.B., C.A. Martin, K. Appa, J. Kudva, and M.N. West, "Smart Wing Wind-Tunnel Test Results," *Industrial and Commercial Applications of Smart Structures Technologies*, Paper 3044-05, Vol. 3044, Society of PhotoOptical Instrumentation Engineers (SPIE), Bellingham, WA, 1997.

119. Scherer, L.B., C.A. Martin, M. West, J.P. Florence, C.C. Wiseman, A.W. Burner, and G.A. Fleming, "DARPA/AFRL/NASA Smart Wing Wind Tunnel Test Results," *Industrial and Commercial Applications of Smart Structures Technologies*, SPIE 3674-28, Vol. 3674, Society of PhotoOptical Instrumentation Engineers (SPIE), Bellingham, WA, 1999, pp. 249–259.

120. Austin, F., W.C. Van Nostrand, M. Siclari, P. Aidala, and R. Clifford, "Design and Performance Predictions of Smart Wing for Transonic Cruise," *Industrial and Commercial Applications of Smart Structures Technologies*, Vol. 2721, Society of PhotoOptical Instrumentation Engineers (SPIE), Bellingham, WA, 1996, pp. 17–25.

121. Yurkovich, R., "Optimum Wing Shape for an Active Flexible Wing," *Proceedings of the 36th Structures, Structural Dynamics, and Materials Conference,* AIAA-95-1220-CP, Part 1, AIAA, Reston, VA, April 1995, pp. 520–530.

122. Pendleton, E., K. Griffin, M. Kehoe, and B. Perry, "A Flight Research Program for Active Aeroelastic Wing Technology," *Proceedings of the 37th Structures, Structural Dynamics, and Materials Conference*, AIAA-96-1574, AIAA, Reston, VA, 1996.

123. Pendleton, E., D. Bessette, P. Field, G. Miller, and K. Griffin, "The Active Aeroelastic Wing Flight Research Program," *Proceedings of the 39th Structures, Structural Dynamics, and Materials Conference*, AIAA-98-1972, AIAA, Reston, VA, 1998.

124. Hopkins, M.A., J.P. Dunne, E.W. Baumann, and E.V. White, "Adaptive Fighter Engine Inlet," *Proceedings of the 40th Structures, Structural Dynamics, and Materials Conference*, AIAA-99-1512, AIAA, Reston, VA, 1999.

125. Park, M., L. Green, R. Montgomery, and D. Raney, "Determination of Stability and Control Derivatives Using Computational Fluid Dynamics and Automatic Differentiation," *Proceedings of the 17th Applied Aerodynamics Conference*, AIAA-99-3136, AIAA, Reston, VA, 1999.

126. Barrett, R., "Active Plate and Missile Wing Development Using DAP Elements," *AIAA Journal*, Vol. 32, No. 3, 1994, pp. 601–609.

127. Barrett, R., "Advanced Low-Cost Smart Fin Technology Evaluation," Final Report to Wright Laboratory, USAF Armament Directorate, Contract No. F08630-93-C-0039, Eglin AFB, December 1993.

128. Heigl, H., W. Hetzler, and E. Lenz, "Guiding Guided Missiles," *Aerospace*, January 1998, pp. 41–46.

129. Priou, A., "Electromagnetic Antenna and Smart Structures," *AGARD Lecture Series 205, Smart Structures and Materials: Implications for Military Aircraft of New Generation*, Paper 11, October 1996, pp. 11-1–11-5.

130. Bartley-Cho, J., K. Alt, D. Coughlin, A. Lockyer, J.N. Kudva, J. Tuss, and A. Goetz, "Development and Testing of a Conformal Load-Bearing, Smart Skin Antenna Structure," *Proceedings of the 40th Structures, Structural Dynamics, and Materials Conference*, AIAA-99-1515, AIAA, Reston, VA, 1999.

131. Hopkins, M.A., J.M. Tuss, A.J. Lockyer, and J.N. Kudva, "Smart Skin Conformal Load-Bearing Antenna and Other Smart Structure Developments," *NATO Workshop on Smart Electromagnetic Antenna Structures*, November 25–26, 1996, 11 pages.

132. Alt, K.H., A.J. Lockyer, C.A. Martin, and J.N. Kudva, "Application for Smart Skin Technologies to the Development of a Conformal Antenna Installation in the Vertical Tail of a Military Aircraft," *Smart Electronics*, Vol. 2448, Society of PhotoOptical Instrumentation Engineers (SPIE), Bellingham, WA, 1995, pp. 42–52.

133. Polites, M., "Digital Avionics," *Aerospace America*, December 1996, pp. 38–39.

134. Barnett, D.M., and S.P. Rawal, "Multifunctional Structures Technology Experiment on Deep Space 1 Mission," *Proceedings of the IEEE Aerospace and Electronic Systems Conference*, Institute of Electrical and Electronics Engineers, Piscataway, NJ, 1999, pp. 13–19.

135. Barnett, D.M., S. Rawal, and K. Rummel, "Multifunctional Structures for Advanced Spacecraft," in preparation.

136. Private communication with Mr. R. Hanson, ITN, January 1999.

137. Wlezien, R.W., G.C. Horner, A.R. McGowan, S.L. Padula, M.A. Scott, R.J. Silcox, and J.O. Simpson, "The Aircraft Morphing Program," *Industrial and Commercial Applications of Smart Structures Technologies*, Vol. 3326, Society of PhotoOptical Instrumentation Engineers (SPIE), Bellingham, WA, 1998, pp. 176–187.

138. Huber, J.E., N.A. Fleck, and M.F. Ashby, "The Selection of Mechanical Actuators Based on Performance Indices," *Proceedings of the Royal Society of London*, Volume A453, Royal Society of London, London, 1997, pp. 2185–2205.

139. Simpson, J.O., Z. Ounaies, and C. Fay, "Polarization and Piezoelectric Properties of a Nitrile Substituted Polyimide," *Materials Research Society Proceedings: Materials for Smart Systems II*, Materials Research Society, Pittsburgh, PA, MRS A98-19626 04-23, Vol. 459, 1997, pp. 59–64.

140. Ounaies, Z., J. Young, J.O. Simpson, and B. Farmer, "Dielectric properties of piezoelectric polyimides," *Materials Research Society Proceedings: Materials for Smart Systems II*, Materials Research Society, Pittsburgh, PA, MRS A98-19626 04-23, Vol. 459, 1997, pp. 53–58.

141. Simpson, J.O., S.A. Wise, R.G. Bryant, R.J. Cano, T.S. Gates, J.A. Hinkley, R.S. Rogowski, and K.S. Whitley, "Innovative Materials for Aircraft Morphing," *Industrial and Commercial Applications of Smart Structures Technologies*, Paper 3326-20, Vol. 3326, Society of PhotoOptical Instrumentation Engineers (SPIE), Bellingham, WA, 1998.

142. TRS Ceramics, Inc., company literature (2820 East College Avenue, Suite J, State College, PA 16801), 1999.

143. Pan, M.J., P. Pertsch, S. Yoshikawa, T.R. Shrout, and V. Vedula, "Electroactive Actuator Materials: Investigations on Stress and Temperature Characteristics," *Smart Materials*, Vol. 3324, Society of PhotoOptical Instrumentation Engineers (SPIE), Bellingham, WA, 1998, pp. 145–153.

144. Tickle, R., and R.D. James, "Magnetic and Magnetomechanical Properties of Ni_2MnGa," *Journal of Magnetism and Magnetic Materials*, in press.

145. James, R.D., and M. Wuttig, "Magnetostriction of Martensite," *Philosophical Magazine A: Physics of Condensed Matter Structure, Defects and Mechanical Properties*, Vol. A77, 1998, pp. 1273–1299.

146. Furuya, Y., N. Hagood, H. Kimura, and T. Watanabe, "Shape Memory Effect and Magnetostriction in Rapidly Solidified Fe- 29.6 at % Pd Alloy," *Materials Transactions, Japan Institute of Metals*, Vol. 39, 1998, pp. 1248–1254.

147. Murray, S.J., R. Hayashi, M. Marioni, S.M. Allen, and R.C. O'Handley, "Magnetic and mechanical properties of FeNiCoTi and NiMnGa magnetic shape memory alloys," in *Smart Materials Technologies*, Vol. 3675, Society of PhotoOptical Instrumentation Engineers (SPIE), Bellingham, WA, 1999, pp. 204–211.

148. Uchino, K., "Shape Memory Ceramics," in *Shape Memory Materials*, K. Otsuka and C.M. Wayman, Eds., Cambridge University Press, Cambridge, UK, 1998, pp. 184–202.

149. Irie, M., "Shape Memory Polymers," in *Shape Memory Materials*, K. Otsuka and C.M. Wayman, Eds., Cambridge University Press, Cambridge, UK, 1998, pp. 203–218.

150. West, J., "Basics of Actuator Technology," *Lasers & Optronics*, September 1993, pp. 21–22.

151. Claus, R.O., "Sensor Instrumentation for Smart Materials and Structures," *Proceedings of the American Society of Mechanical Engineers (ASME) Winter Annual Conference*, AD-Vol. 52, American Society of Mechanical Engineers, New York, 1996, pp. 463–469.

152. Murphy, K.A., M.F. Gunther, R.G. May, R.O. Claus, T.A. Tran, J.A. Greene, and P.G. Duncan, "EFPI Sensor Manufacturing and Applications," *Industrial and Commercial Applications of Smart Structures Technologies*, Vol. 2721, Society of PhotoOptical Instrumentation Engineers (SPIE), Bellingham, WA, 1996, pp. 476–482.

153. Dunphy, J.A., "Feasibility Study Concerning Optical Fiber Sensor Vibration Monitoring Subsystem," *Industrial and Commercial Applications of Smart Structures Technologies*, Vol. 2721, Society of PhotoOptical Instrumentation Engineers (SPIE), Bellingham, WA, 1996, pp. 483–492.

154. Brown, T., K. Wood, B. Childers, B. Cano, B. Jensen, and R. Rogowski, "Fiber Optic Sensors for Health Monitoring of Morphing Aircraft," *Industrial and Commercial Applications of Smart Structures Technologies,* Vol. 3674, Society of PhotoOptical Instrumentation Engineers (SPIE), Bellingham, WA, 1999, pp. 60–71.

155. Giurgiutiu, V., and C.A. Rogers, "Power and Energy Characteristics of Solid-State Induced-Strain Actuators for Static and Dynamic Applications," *Journal of Intelligent Material Systems and Structures*, Vol. 8, September 1997, pp. 738–750.

156. Giurgiutiu, V., R. Pomirleanu, and C.A. Rogers, "Energy-Based Comparison of Solid-State Actuators," University of South Carolina, Department of Mechanical Engineering Report #USC-ME-LAMSS-2000-102, March 1, 2000.

157. Jacobs, J.H., "Synthesis and Processing of Intelligent Cost-Effective Structures: A Final Review of the ARPA SPICES Program," *Industrial and Commercial Applications of Smart Structures Technologies,* Vol. 2721, Society of PhotoOptical Instrumentation Engineers (SPIE), Bellingham, WA, 1996, pp. 167–188.

158. Bridger, K., L. Jones, F. Poppe, S. Brown, and S.R. Winzer, "High-Force, Co-fired Multilayer Actuators," *Industrial and Commercial Applications of Smart Structures Technologies,* Vol. 2721, Society of PhotoOptical Instrumentation Engineers (SPIE), Bellingham, WA, 1996, pp. 341–352.

159. Gentilman, R.L., D. Fiore, H. Pham-Nguyen, W. Serwatka, B.G. Pazol, C.D. Near, P. McGuire, and L. Bowen, "1–3 Piezocomposite Smart Panels for Active Surface Control," *Industrial and Commercial Applications of Smart Structures Technologies*, Vol. 2721, Society of PhotoOptical Instrumentation Engineers (SPIE), Bellingham, WA, 1996, pp. 234–239.

160. French, J.D., G.E. Weitz, J.E. Luke, and R.B. Cass, "Production of Piezoelectric Fibers for Smart Materials and Active Control Devices," *Industrial and Commercial Applications of Smart Structures Technologies,* Paper 3044-39, Vol. 3044, Society of PhotoOptical Instrumentation Engineers (SPIE), Bellingham, WA, 1997.

161. Haertling, G.H., "RAINBOW Ceramics—A New Type of Ultra-High-Displacement Actuator," *American Ceramic Society Bulletin*, Vol. 73, 1994, pp. 93–96.

162. Hooker, M.W., "Properties and Performance of RAINBOW Piezoelectric Actuator Stacks," *Industrial and Commercial Applications of Smart Structures Technologies,* Vol. 3044, Society of PhotoOptical Instrumentation Engineers (SPIE), Bellingham, WA, 1997, pp. 413–420.

163. Dausch, D.E., and S.A. Wise, "Compositional Effects on Electromechanical Degradation of RAINBOW Actuators," NASA-TM 206282, NASA-Langley Research Center, Hampton, VA, 1998.

164. Wise, S.A., R.C. Hardy, and D.E. Dausch, "Design and Development of an Optical Path Difference Scan Mechanism for Fourier Transform Spectrometers Using High Displacement RAINBOW Actuators," *Industrial and Commercial Applications of Smart Structures Technologies,* Vol. 3044, Society of PhotoOptical Instrumentation Engineers (SPIE), Bellingham, WA, 1997, pp. 342–349.

165. Hellbaum, R.F., R.G. Bryant, R.L. Fox, A. Jalink, W.W. Rohrbach, and J.O. Simpson, "Thin Layer Composite Unimorph and Ferroelectric Driver and Sensor," U.S. Patent 5,632,840, May 27, 1997.

166. Bryant, R.G., "Thunder Actuators," *5th Annual Workshop: Enabling Technologies for Smart Aircraft Systems*, NASA-Langley Research Center, Hampton, VA, May 14–16, 1996.

167. Li, G., and G.H. Haertling, "The Piezoelectric, Pyroelectric and Photoelectronic: Properties of PLZT Rainbow Ceramics," *Proceedings of the 10th IEEE International Symposium on Application of Ferroelectrics*, Vol. 2, Institute of Electrical and Electronic Engineers, Piscataway, NJ, 1996, pp. 907–910.

168. Dausch, D.E., "Ferroelectric Polarization Fatigue in PZT-Based RAINBOWs and Bulk Ceramics," *Journal of the American Ceramics Society,* Vol. 80, No. 9, 1997, pp. 2355–2360.

169. Pinkerton, J.L., A.R. McGowan, R.W. Moses, R.C. Scott, and J. Heeg, "Controlled Aeroelastic Response and Airfoil Shaping Using Adaptive Materials and Integrated Systems," *Industrial and Commercial Applications of Smart Structures Technologies*, Paper 3326-20, Vol. 3326, Society of PhotoOptical Instrumentation Engineers (SPIE), Bellingham, WA, 1998.

170. Pinkerton, J.L., and R.W. Moses, "A Feasibility Study To Control Airfoil Shape Using THUNDER," NASA TM-4767, NASA-Langley Research Center, Hampton, VA, November 1997.

171. Kim, C., A. Glazounov, D. Flippen, A. Pattnaik, Q. Zhang, and D. Lewis, "Piezoelectric Ceramic Assembly Tubes for Torsional Actuators," *Smart Materials*, Vol. 3675, Society of PhotoOptical Instrumentation Engineers (SPIE), Bellingham, WA, 1999, pp. 53–62.

172. Van Humbeeck, J., D. Reynaerts, and J. Peirs, "New Opportunities for Shape Memory Alloys for Actuators, Biomedical Engineering, and Smart Materials," *Materials Technology*, Vol. 11, No. 2, 1996, pp. 55–61.

173. Girshovich, S., L. Shikhamanter, and V. Weissberg, "The Application of Shape Memory Actuators in Adaptive Wings," *Proceedings of the Israel Annual Conference on Aerospace Sciences, 37th*, A97-25510 06-01, Technion-Israel Institute of Technology, Haifa, Israel, pp. 152–153.

174. Schetky, L.M., and B.M. Steinetz, "Shape Memory Alloy Adaptive Control of Gas Turbine Engine Compressor Blade Tip Clearance," *Industrial and Commercial Applications of Smart Structures Technologies*, Paper 3326-36, Vol. 3326, Society of PhotoOptical Instrumentation Engineers (SPIE), Bellingham, WA, 1998, pp. 346–354.

175. Weisensel, G.N., and T.D. Pierce, "High-Authority Smart Material Integrated Electric Actuator," *Industrial and Commercial Applications of Smart Structures Technologies*, Paper 3044-37, Vol. 3044, Society of PhotoOptical Instrumentation Engineers (SPIE), Bellingham, WA, 1997.

176. Weisensel, G.N., T.T. Hanses, and W.D. Hrbek, "High-Power Ultrasonic TERFENOL–D Transducers Enable Commercial Applications," *Industrial and Commercial Applications of Smart Structures Technologies*, Paper 3326-46, Vol. 3326, Society of PhotoOptical Instrumentation Engineers (SPIE), Bellingham, WA, 1998, pp. 450–458.

177. Weisensel, G.N., O.D. McMasters, and R.G. Chave, "Cryogenic Magnetostrictive Transducers and Devices for Commercial, Military, and Space applications," *Industrial and Commercial Applications of Smart Structures Technologies*, Paper 3326-47, Vol. 3326, Society of PhotoOptical Instrumentation Engineers (SPIE), Bellingham, WA, 1998, pp. 459–471.

178. Rusovici, R., V. Giurgiutiu, and C.A. Rogers, "Experimental Study of Hydraulically Amplified, High Displacement, Induced-Strain Actuators, Proof of Concept Demonstrator," *Proceedings of the American Society of Mechanical Engineers (ASME) Winter Annual Conference*, AD-Vol. 52, American Society of Mechanical Engineers, New York, NY, 1996, pp. 567–574.

179. Lee, G.B., C.M. Ho, F. Jiang, C. Liu, T. Tsao, Y.C. Tai, and F. Scheuer, "Control of Roll Moment by MEMS," *Proceedings of the American Society Of Mechanical Engineers (ASME) Winter Annual Conference*, AD-Vol. 52, American Society of Mechanical Engineers, New York, NY, 1996, pp. 797–803.

180. Glezer, A., "Synthetic Jet Actuators for Shear Flow Control, Part I: Synthetic Jet Technology," *5th Annual Workshop: Enabling Technologies for Smart Aircraft Systems*, NASA-Langley Research Center, Hampton, Virginia, May 14–16, 1996.

181. McGowan, A.R., "A Feasibility Study on Using Shunted Piezoelectrics to Reduce Aeroelastic Response," *Industrial and Commercial Applications of Smart Structures Technologies*, SPIE 3674-20, Vol. 3674, Society of PhotoOptical Instrumentation Engineers (SPIE), Bellingham, WA, 1999.

182. Wu, S.Y., and A.S. Bicos, "Structural Vibration Damping Experiments Using Improved Piezoelectric Shunts," *Passive Damping and Isolation,* Vol. 3045, Society of PhotoOptical Instrumentation Engineers (SPIE), Bellingham, WA, 1997, pp. 40–50.

183. Belvin, K., G. Horner, R. Hardy, D. Armstrong, and D. Rosenbaum, "Integration Issues for High-Strain Actuation Applications," *Industrial and Commercial Applications of Smart Structures Technologies*, Paper 3326-20, Vol. 3326, Society of PhotoOptical Instrumentation Engineers (SPIE), Bellingham, WA, 1998.

184. Joshi, S.P., and W.S. Chan, "Fabrication and Curing of Laminates With Multiple Embedded Piezoceramic Sensors and Actuators," *Proceedings of the ADPA/AIAA/ASME/SPIE Conference on Active Materials and Adaptive Structures*, Institute of Physics Publishing, Bristol, UK, 1991, pp. 701–705.

185. Rodgers, J.P., and N.W. Hagood, "Manufacture of Adaptive Composite Plates Incorporating Piezoelectric Fiber Composite Plies," *Proceedings of the 36th Structures, Structural Dynamics, and Materials Conference and Adaptive Structures Forum*, AIAA-95-1096-CP, AIAA, Reston, VA, 1995, pp. 2824–2835.

186. Trottier, M., F. Millet Day, H.E. Duryea, J.R. Dunphy, G. Koopman, and B.F. Carpenter, "Performance of Integrated Fiber Optic, Piezoelectric, and Shape Memory Alloy Actuator/Sensors in Thermoset Composites," *Industrial and Commercial Applications of Smart Structures Technologies*, Paper 2447-27, Vol. 2447, Society of PhotoOptical Instrumentation Engineers (SPIE), Bellingham, WA, 1995.

187. Hom, C.L., and N. Shankar, "A Fully Coupled Constitutive Model for Electrostrictive Ceramic Materials," *Journal of Intelligent Material Systems and Structures*, Vol. 5, November 1994, pp. 795–801.

188. Jia, H., F. Lalande, and C.A. Rogers, "Review of Constitutive Modeling of Shape Memory Alloys," *Proceedings of the American Society of Mechanical Engineers (ASME) Winter Annual Conference*, AD-Vol. 52, American Society of Mechanical Engineers, New York, NY, November 1996, pp. 585–591.

189. Brinson, L.C., A.M. Bekker, and S. Hwang, "Temperature-Induced Deformation in Shape Memory Alloys," in *Active Materials and Smart Structures*, Vol. 2427, Society of PhotoOptical Instrumentation Engineers (SPIE), Bellingham, WA, 1995, pp. 234–244.

190. Babuska, V., and B.D. Freed, "Finite Element Modeling of Composite Piezoelectric Structures With MSC/NASTRAN," *Smart Structures and Integrated Systems*, Paper 3041-60, Vol. 3041, Society of PhotoOptical Instrumentation Engineers (SPIE), Bellingham, WA, 1997.

191. Taleghani, B.K., and J.F. Campbell, "Non-Linear Finite Element Modeling of THUNDER Piezoelectric Actuator," *Smart Structures and Integrated Systems*, Paper 3668-52, Vol. 3668, Society of PhotoOptical Instrumentation Engineers (SPIE), Bellingham, WA, 1999, pp. 555–566.

192. Hauch, R., "An Industrial Approach to Static and Dynamic Finite Element Modeling of Composite Structures With Embedded Actuators," *Smart Structures and Integrated Systems*, Vol. 2443, Society of PhotoOptical Instrumentation Engineers (SPIE), Bellingham, WA, 1995, pp. 458–469.

193. Seeley, C.E., "Analysis and Optimization of Smart Composite Structures Including Debonding," Ph.D. Dissertation, Arizona State University, May 1997.

194. Freed, B.D., and V. Babuska, "Finite Element Modeling of Composite Piezoelectric Structures With MSC/NASTRAN," *Smart Structures and Integrated Systems*, Paper 3041-60, Vol. 3041, Society of PhotoOptical Instrumentation Engineers (SPIE), Bellingham, WA, 1997.

195. Crawley, E.F., and J. de Luis, "Use of Piezoelectric Actuators as Elements of Intelligent Structures," *AIAA Journal*, Vol. 25, No. 10, 1987, pp. 1373–1385.

196. Ha, S.K., C.H. Keilers, and F.K. Chang, "Finite Element Analysis of Composite Structures Containing Distributed Piezoceramic Sensors and Actuators," *AIAA Journal,* Vol. 30, No. 3, March 1992, pp. 2323–2330.

197. Belvin, W.K., "Spacecraft Jitter Attenuation Using Embedded Piezoelectric Actuators," *Proceedings of the International Forum on Aeroelasticity and Structural Dynamics*, Confederation of European Aerospace Societies (CEAS) 1995, 16 pages.

198. Sang, L.H., *MSC/NASTRAN Handbook for Non-Linear Analysis: Based on Version 67*, The MacNeil Schwendler Corporation, Los Angeles, CA, 1992.

199. Pototzky, T.S., "Analytical Model Development for Piezoelectric-Structural Interactions," NASA Contractor Report.

200. Adams, W.M., Jr., and S.T. Hoadley, "ISAC: A Tool for Aeroservoelastic Modeling and Analysis," NASA-TM-109031, NASA-Langley Research Center, Hampton, VA, December 1993.

201. Nam, C., and K. Youdan, "Optimal Design of Composite Lifting Surface for Flutter Suppression With Piezoelectric Actuators," *AIAA Journal*, Vol. 33, No. 10, October 1995, pp. 1897–1904.

202. Heeg, J., "Analytical and Experimental Investigation of Flutter Suppression via Piezoelectric Actuation," NASA TP-3241, NASA-Langley Research Center, Hampton, VA, March 1993.

203. Regelbrugge, M.E., "Design Issues for Electrostrictive Actuators," *5th International Conference on Adaptive Structures*, Technomic Publishing Co., Inc., Lancaster, PA, 1995, pp. 555–568.

204. *MATLAB, High Performance Numeric Computation and Visualization Software: Reference Guide,* The MathWorks, Inc., Natick, MA, 1992.

205. Johnson, W., "CAMRAD II, Comprehensive Analytical Model of Rotorcraft Aerodynamics and Dynamics," Johnson Aeronautics, Palo Alto, California, 1994.

206. Lim, K.B., R.C. Lake, and J. Heeg, "Selection of Piezoceramic Actuators on an Experimental Flexible Wing," *Proceedings of the AIAA Guidance, Navigation and Control Conference*, AIAA-96-3758, AIAA, Reston, VA, 1996.

207. Lin, C.Y., "Strain-Actuated Aeroelastic Wing," Ph.D. Dissertation, Massachusetts Institute of Technology, May 1997.

208. Varadan, V.V., Ed., *Mathematics and Control in Smart Structures*, Vol. 3323, Society of PhotoOptical Instrumentation Engineers (SPIE), Bellingham, WA, 1998, 756 pages.

209. Varadan, V.V., editor, *Mathematics and Control in Smart Structures*, Vol. 3667, Society of PhotoOptical Instrumentation Engineers (SPIE), Bellingham, WA, 1999.

210. Chou, K.C., D.S. Flamm, G.S. Guthart, and R.M. Ueberschaer, "Multiscale Approach to the Control of Smart Structures," *Industrial and Commercial Applications of Smart Structures Technologies*, Vol. 2721, Society of PhotoOptical Instrumentation Engineers (SPIE), Bellingham, WA, 1996, pp. 94–105.

211. Studt, T., "Wavelet Technology Offers Designers Alternative to Fourier Analysis," *R&D Magazine*, May 1996, p. 51.

212. Studt, T., "Neural Networks: Computer Toolbox for the 90's," *R&D Magazine*, September 1991, pp. 36–42.

213. Damle, R., V. Rao, and F. Kern, "Multivariable Neural Network Based Controllers for Smart Structures," *Journal of Intelligent Material Systems and Structures*, Vol. 6, July 1995, pp. 516–528.

214. Manning, R.A., "Damage Detection in Adaptive Structures Using Neural Networks," *Proceedings of the Adaptive Structures Forum*, AIAA-94-1752-CP, AIAA, Reston, VA, 1994, pp. 160–172.

215. Carneal, J.P., and C.R. Fuller, "A Biologically Inspired Controller for Sound and Vibration Control," *Proceedings of the Adaptive Structures Forum*, AIAA-94-1752-CP, AIAA, Reston, VA, 1994, pp. 474–484.

216. Kwak, M.K., and D. Sciulli, "Fuzzy-Logic Based Vibration Suppression Control Experiments on Active Structures," *Proceedings of the 36th Structures, Structural Dynamics, and Materials Conference*, AIAA-95-1085-CP, Part 4, AIAA, Reston, VA, April 1995, pp. 2319–2327.

217. Geng, Z.J., L. Haynes, B.K. Wada, and J. Garba, "Active Vibration Isolation Using Fuzzy CMAC Neural Networks," *Proceedings of the 36th Structures, Structural Dynamics, and Materials Conference*, AIAA-95-1084-CP, Part 4, AIAA, Reston, VA, April 1995, pp. 2308–2318.

218. QRDC, Inc., company literature (P.O. Box 562, Excelsior, MN 55331), 1996.

219. Nye, T., S. Casteel, S. Navarro, and B. Kraml, "Experiences With Integral Microelectronics on Smart Structures for Space," *Smart Electronics*, Vol. 2448, Society of PhotoOptical Instrumentation Engineers (SPIE), Bellingham, WA, 1995, pp. 193–203.

220. Zvonar, G.A., J. Luan, F.C. Lee, D.K. Lindner, S. Kelly, D. Sable, and T. Schelling, "High-Frequency Switching Amplifiers for Electrostrictive Actuators," *Industrial and Commercial Applications of Smart Structures Technologies,* Vol. 2721, Society of PhotoOptical Instrumentation Engineers (SPIE), Bellingham, WA, 1996, pp. 465–475.

221. "All-Plastic Battery," *NASA Tech Briefs*, October 1996, p. 26.

222. Jose, K.A., V.K. Varadan, and V.V. Varadan, "Tunable and Electronically Steerable Microstrip Antenna," *Smart Electronics,* Vol. 3673, Society of PhotoOptical Instrumentation Engineers (SPIE), 1999, pp. 195–200.

223. Piscotty, D., K.A. Jose, V.V. Varadan, and V.K. Varadan, "Design and Development of 150 MHz Wireless Telemetry System for MEMS–IDT Based Sensor," *Smart Electronics,* Vol. 3673, Society of PhotoOptical Instrumentation Engineers (SPIE), Bellingham, WA, 1999, pp. 165–172.

224. Varadan, V.K., and V.V. Varadan, "Smart Structures, MEMS, and Smart Electronics for Aircraft," *AGARD Lecture Series 205, Smart Structures and Materials: Implications for Military Aircraft of New Generation*, October 1996, Paper 8, pp. 8-1–8-19.

225. Lincoln, J.W., "Structural Technology Transition to New Aircraft," *Proceedings From the 14th Symposium of the International Committee on Aeronautical Fatigue*, Ottawa, Canada, 1987.

226. Veitch, L.C., "Assessment of the DARPA Affordable Polymer Matrix Composites Programs," Institute for Defense Analyses, IDA Document D-2068, July 1997.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	September 2000	Final —September 1998–September 2000

4. TITLE AND SUBTITLE
An Assessment of Smart Air and Space Structures: Demonstrations and Technology

5. FUNDING NUMBERS
IDA Central Research Program
CRP-2038

6. AUTHOR(S)
Janet M. Sater, C. Robert Crowe, Richard Antcliff, Alok Das

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Institute for Defense Analyses
1801 N. Beauregard St.
Alexandria, VA 22311-1772

8. PERFORMING ORGANIZATION REPORT NUMBER
IDA Paper P-3552

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT ***(Maximum 180 words)***

During the past decade, the multidisciplinary field of smart materials and structures has experienced rapid growth in terms of individual technologies and applications. The integration of sensors, actuators, and controllers with structures that enable adaptation to environmental and operational conditions has progressed to such a point that numerous systems applications are being demonstrated. This paper reviews the current status, results to date, and issues associated with several of these projects. This review focuses on realistic sub- or full-scale systems demonstrations and relevant characterization and testing in the following areas: structural health monitoring, noise and vibration suppression [e.g., launch isolation, precision pointing, interior noise, tail buffet, wing flutter, and helicopter blade-vortex interaction (BVI)], shape control, and multifunctional structural concepts for spacecraft and launch vehicles, aircraft, and rotorcraft. These demonstrations focus on showing potential system-level performance improvements using smart technologies in realistic structures. The status of several individual technologies important to achieving the ultimate objective of a "smart" system—actuator materials, devices (sensors and actuators), electronics, control, modeling and analyses, and integration (at the manufacturing and overall system levels)—is also addressed in some detail. Included in this discussion is an assessment of their respective technology readiness levels.

14. SUBJECT TERMS
magnetorestrictives, piezoelectric ceramics, shape memory alloy (SMA), smart materials, smart structures

15. NUMBER OF PAGES
127

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	SAR

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102